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(54) **OPTICAL FIBER CONFIGURATIONS FOR TRANSMISSION OF LASER ENERGY OVER GREAT DISTANCES**

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(58) **Field of Classification Search**
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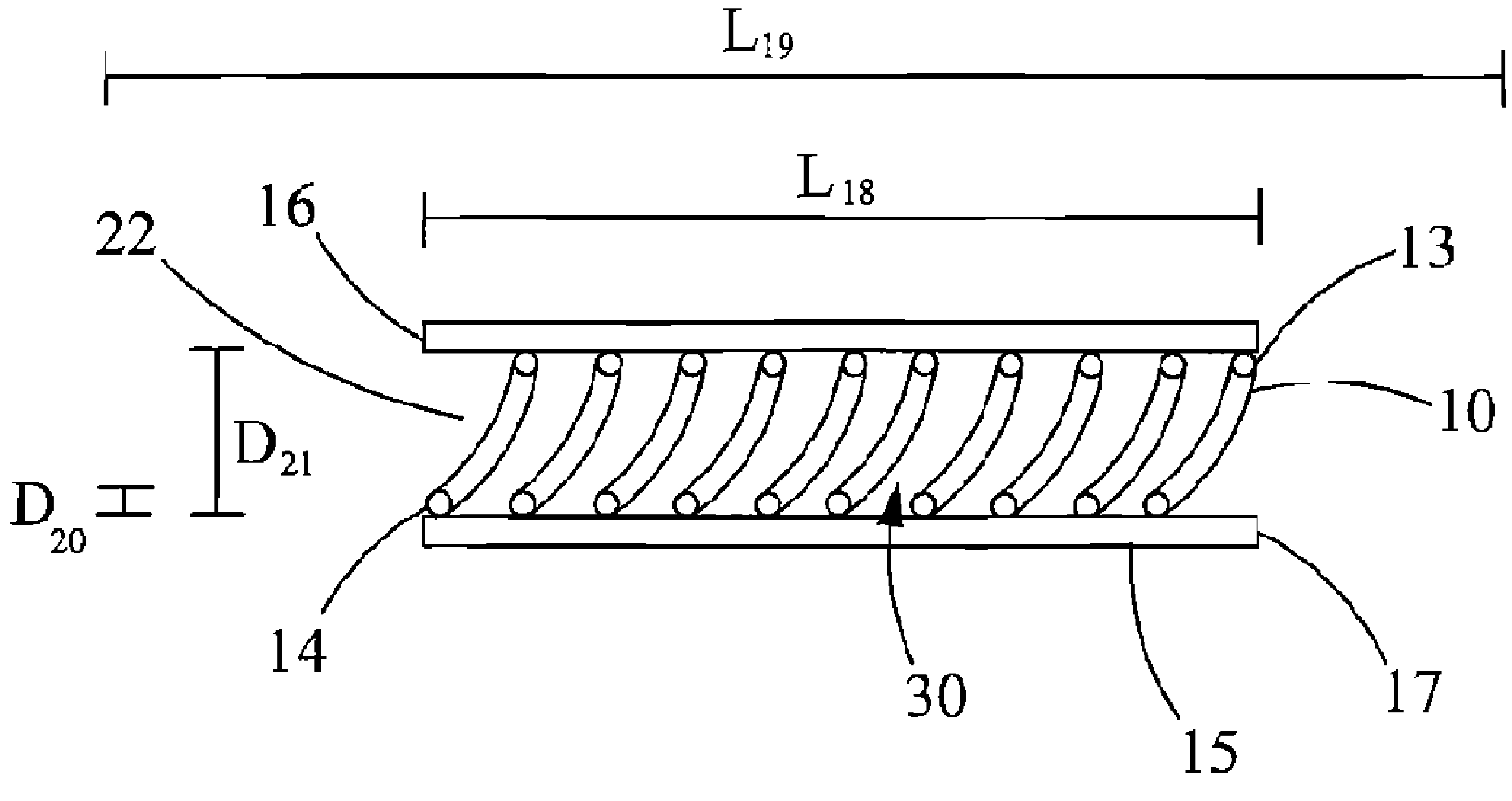
(57) **ABSTRACT**

There are provided optical fiber configurations that provide for the delivery of laser energy, and in particular, the transmission and delivery of high power laser energy over great distances. These configurations further are hardened to protect the optical fibers from the stresses and conditions of an intended application. The configurations provide means for determining the additional fiber length (AFL) need to obtain the benefits of such additional fiber, while avoiding bending losses.

11 Claims, 7 Drawing Sheets



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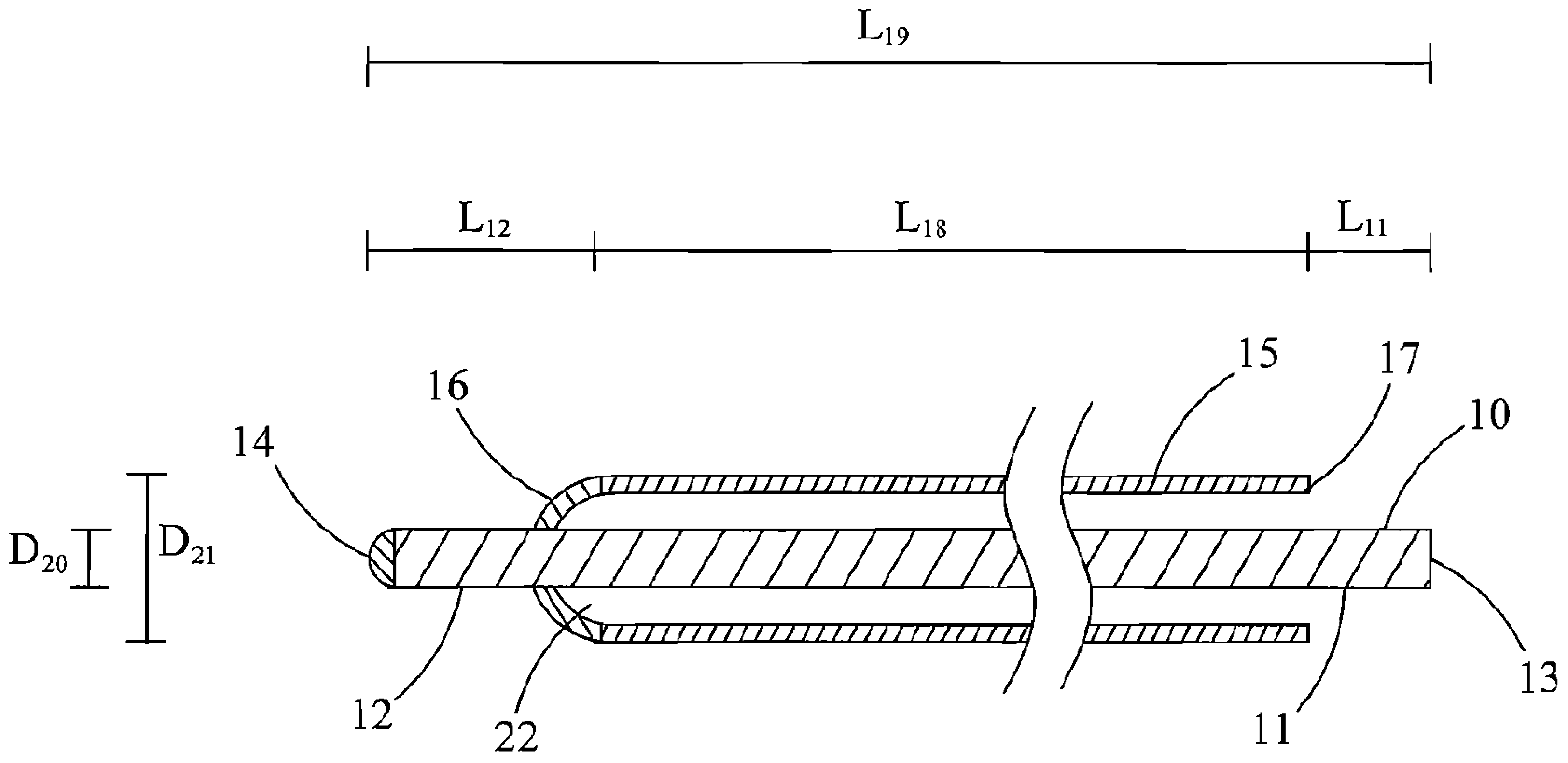

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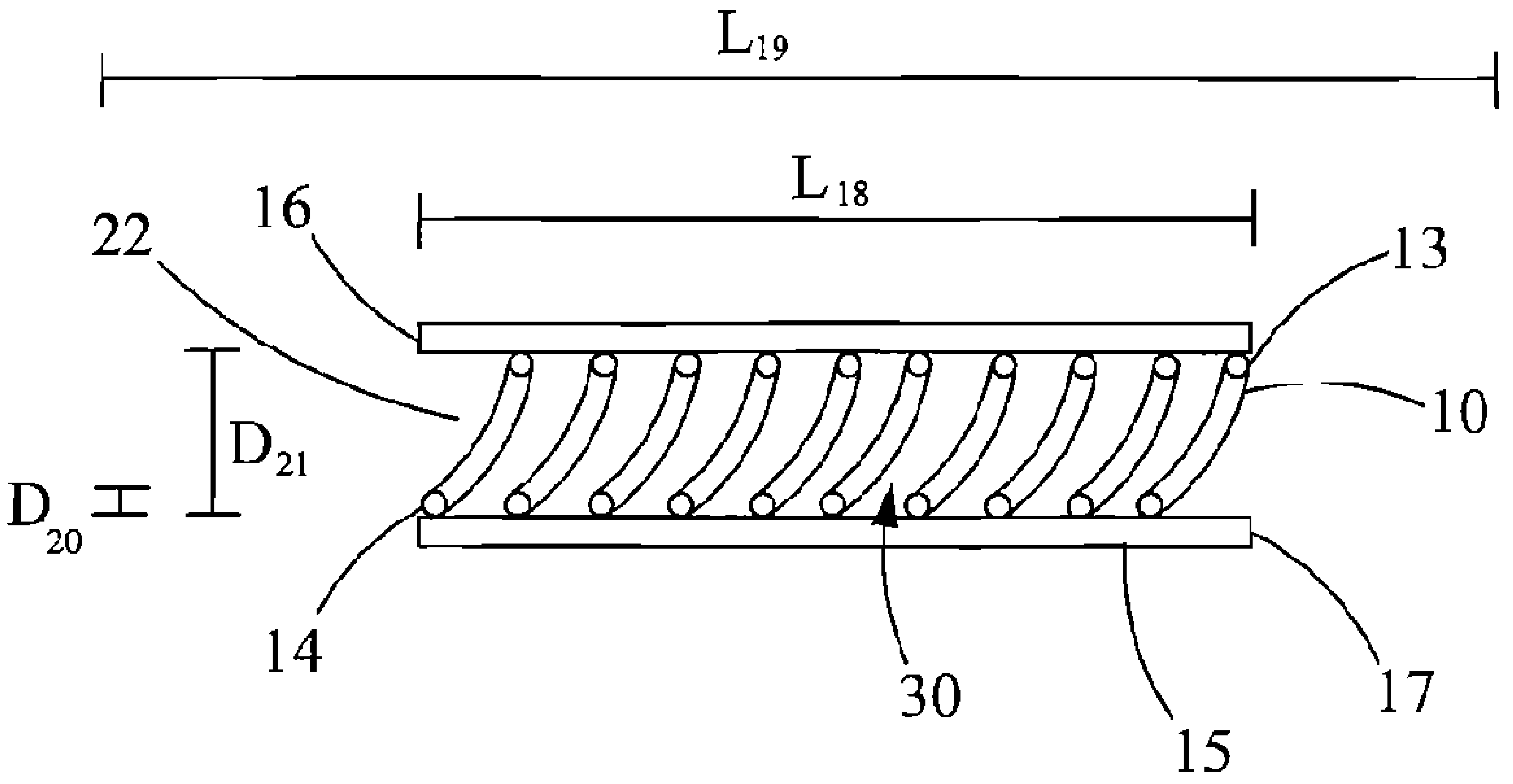

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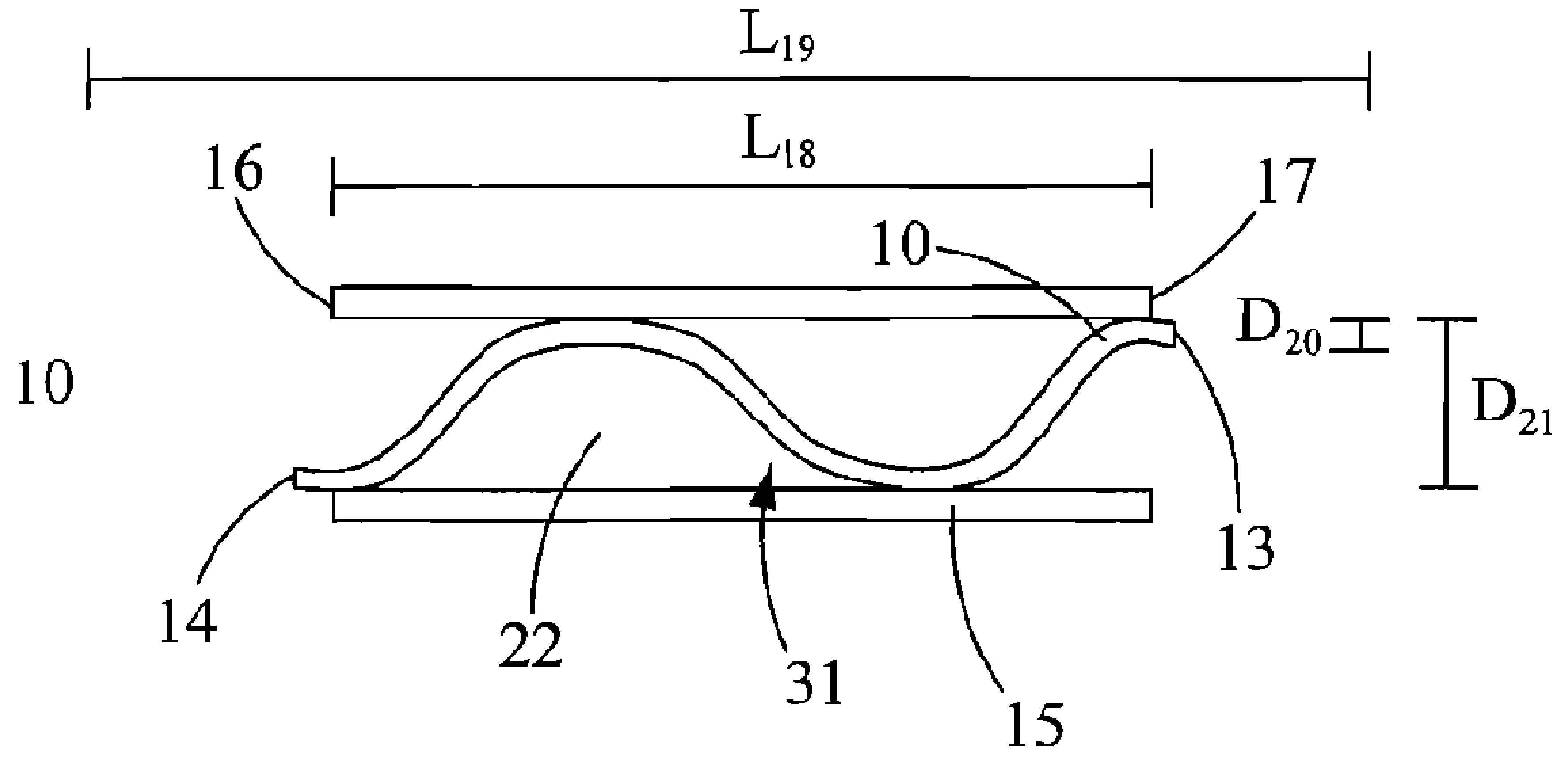

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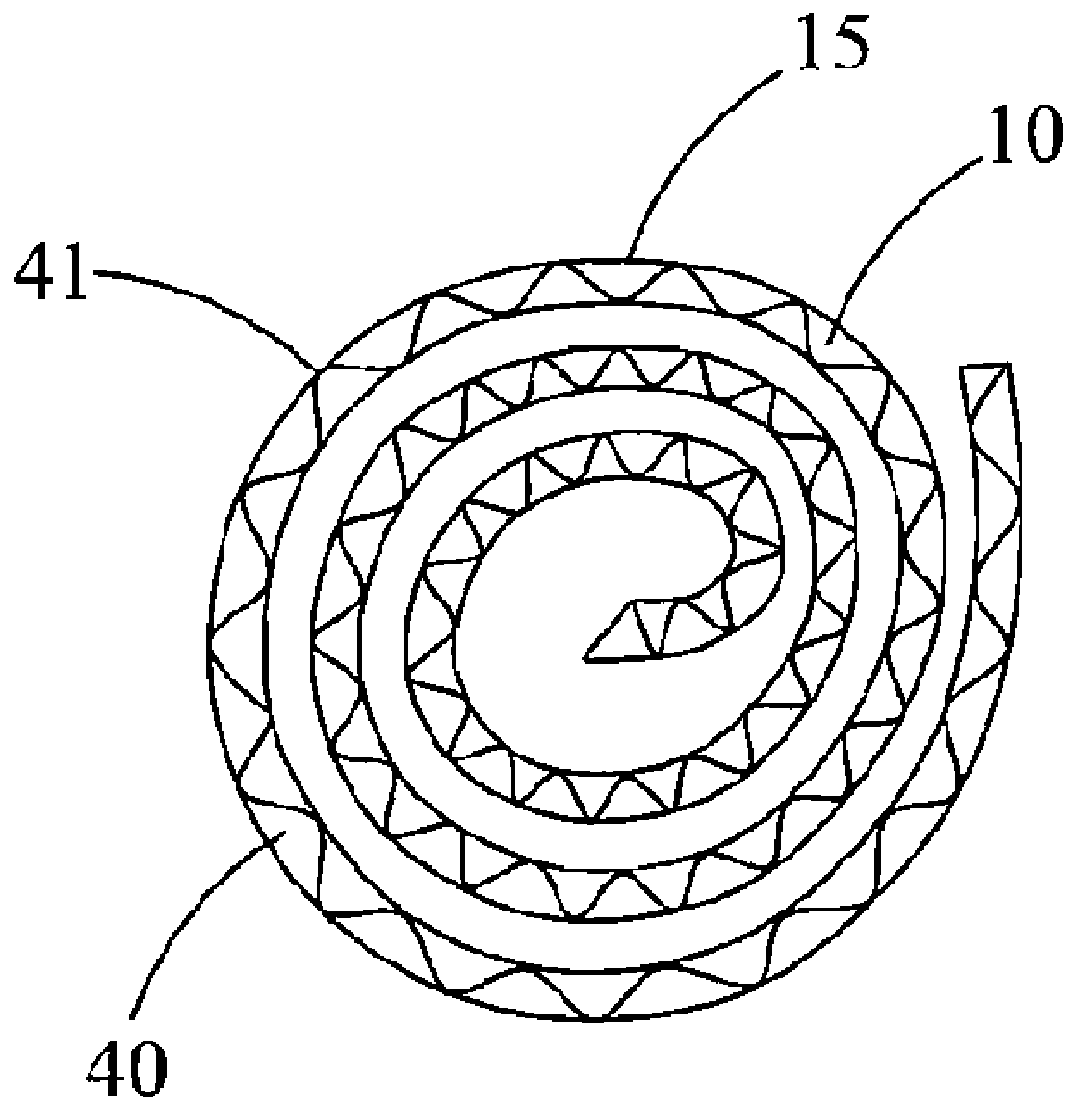

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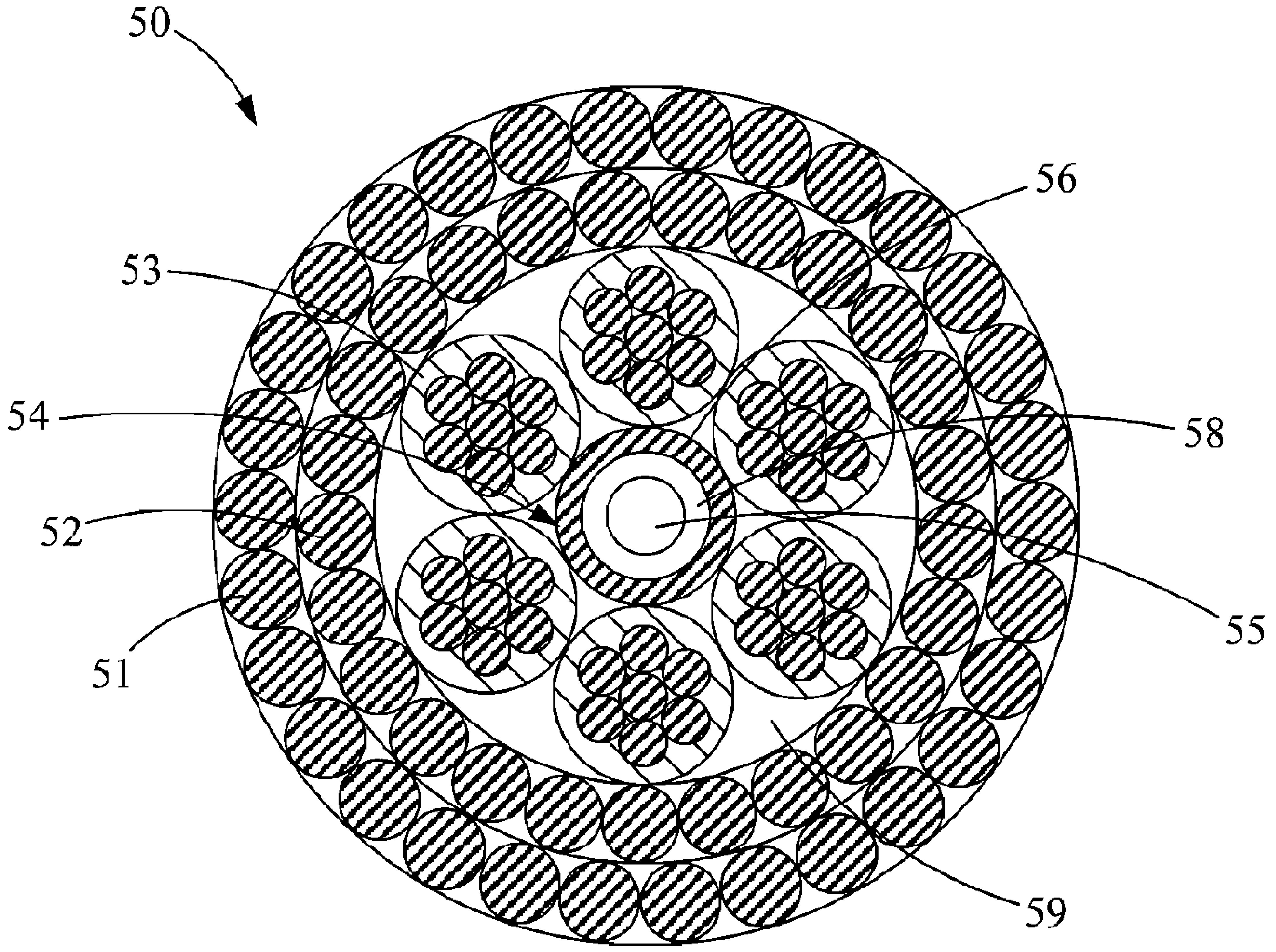

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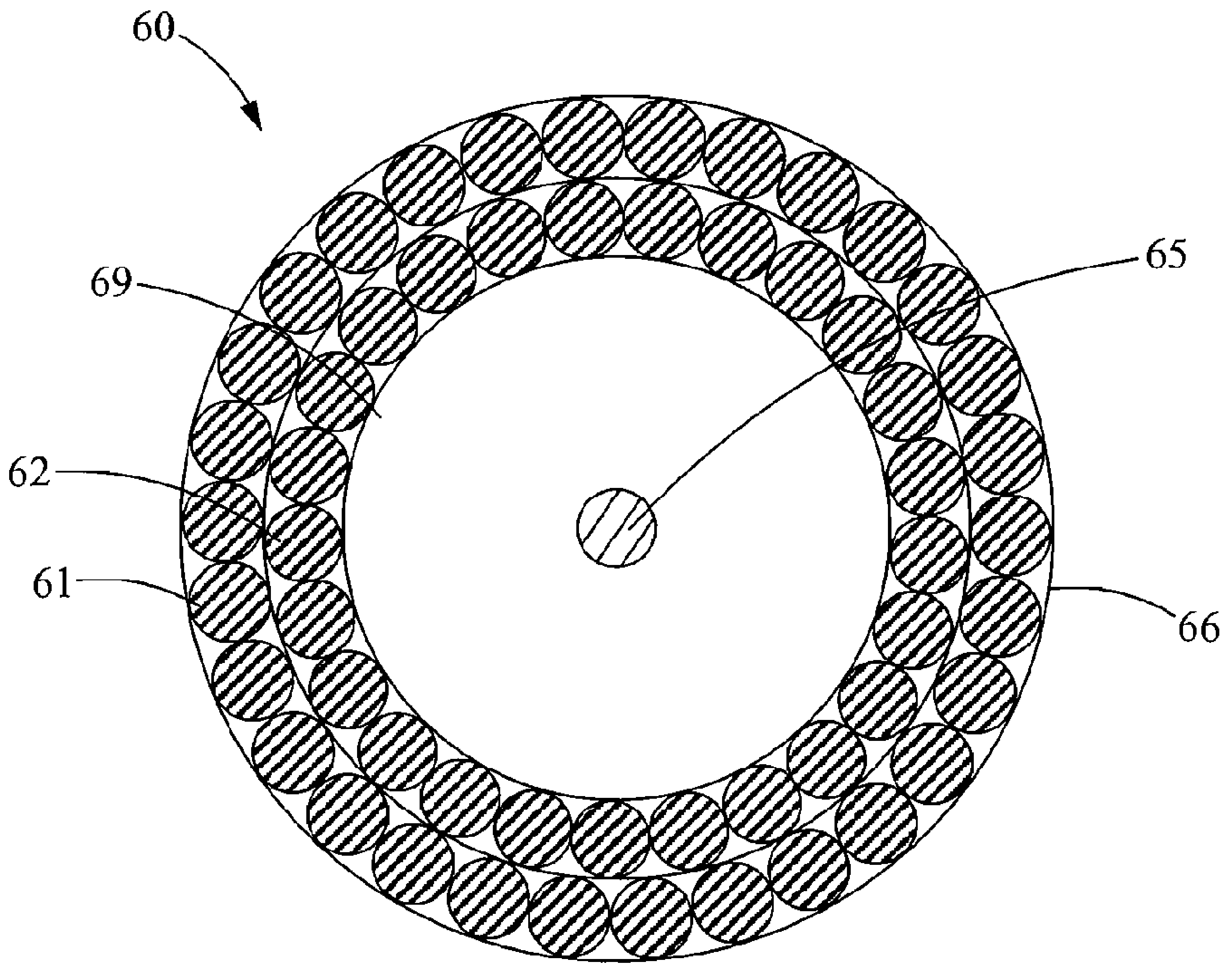

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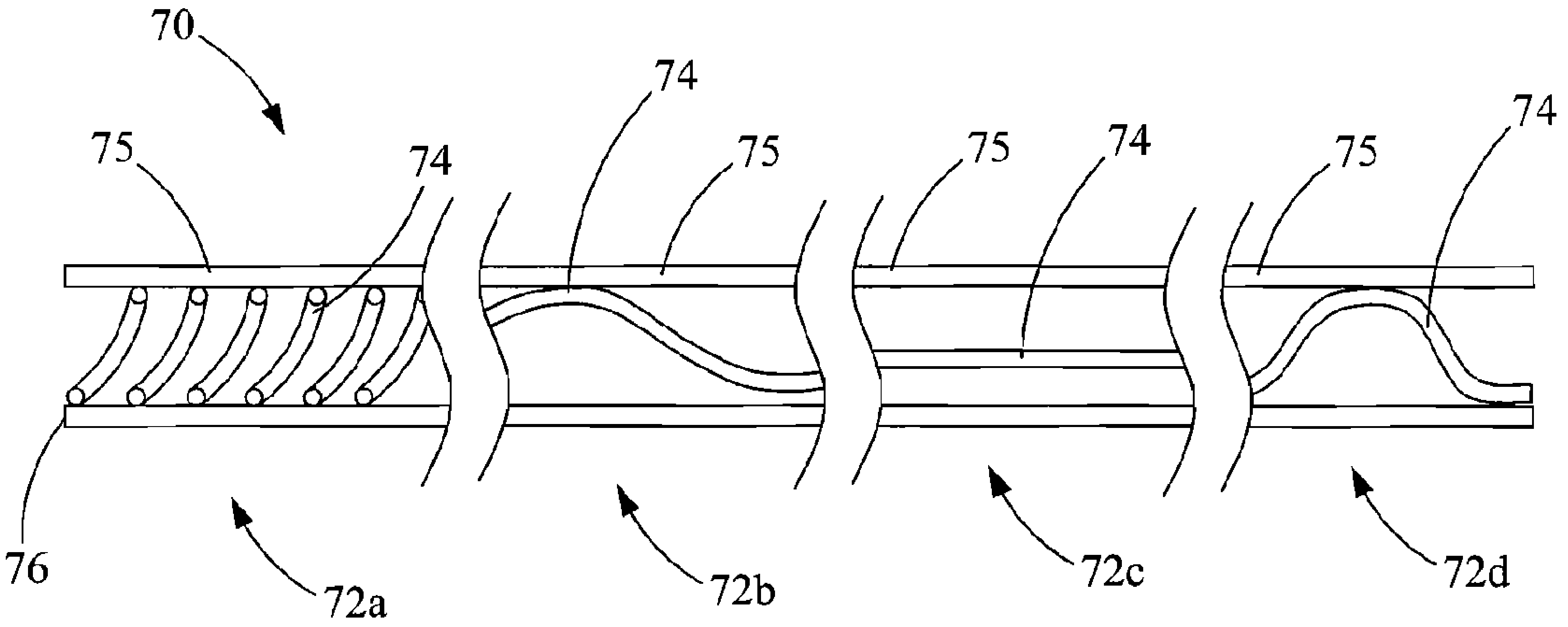

Fig. 7

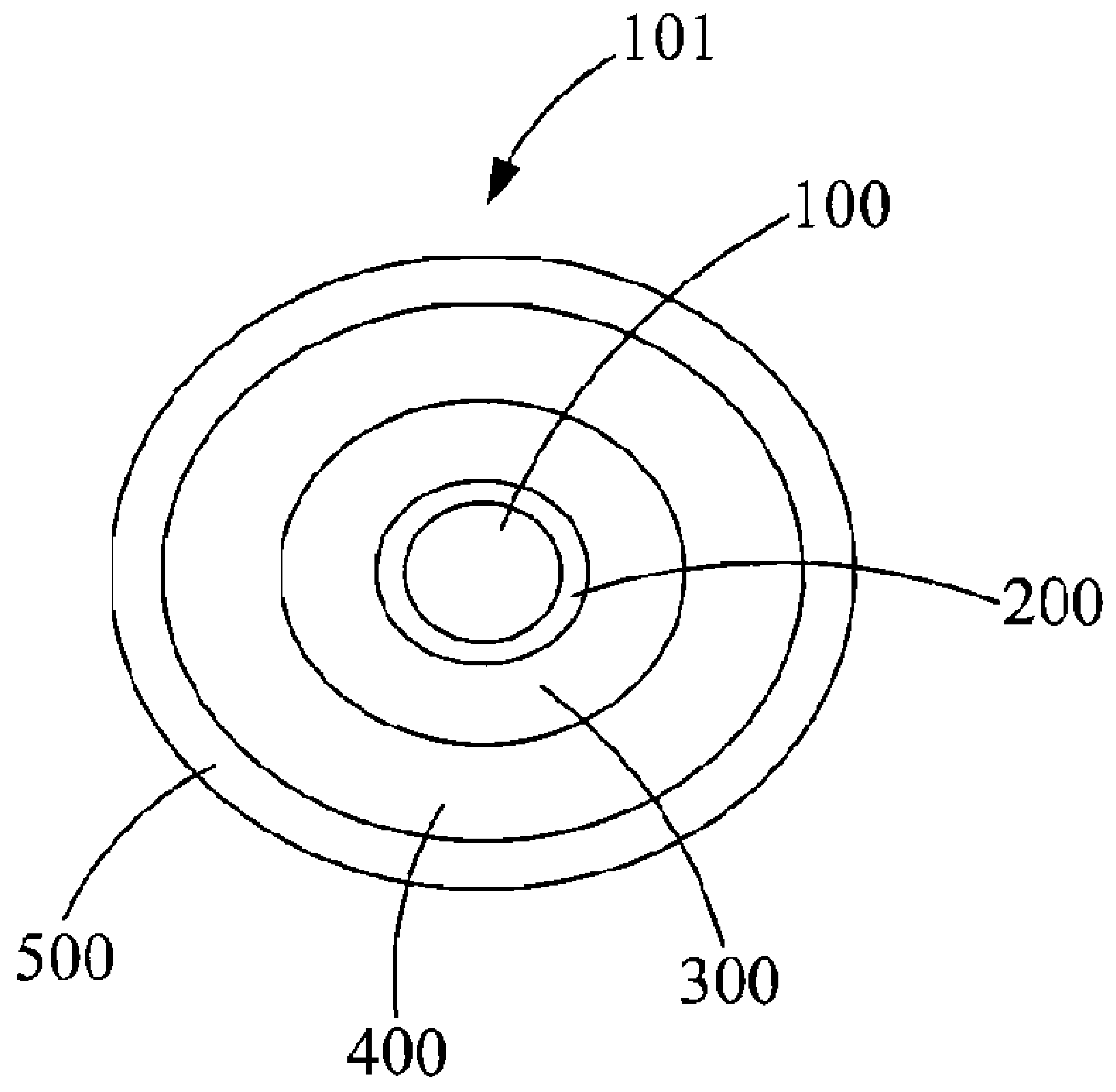

Fig. 8A

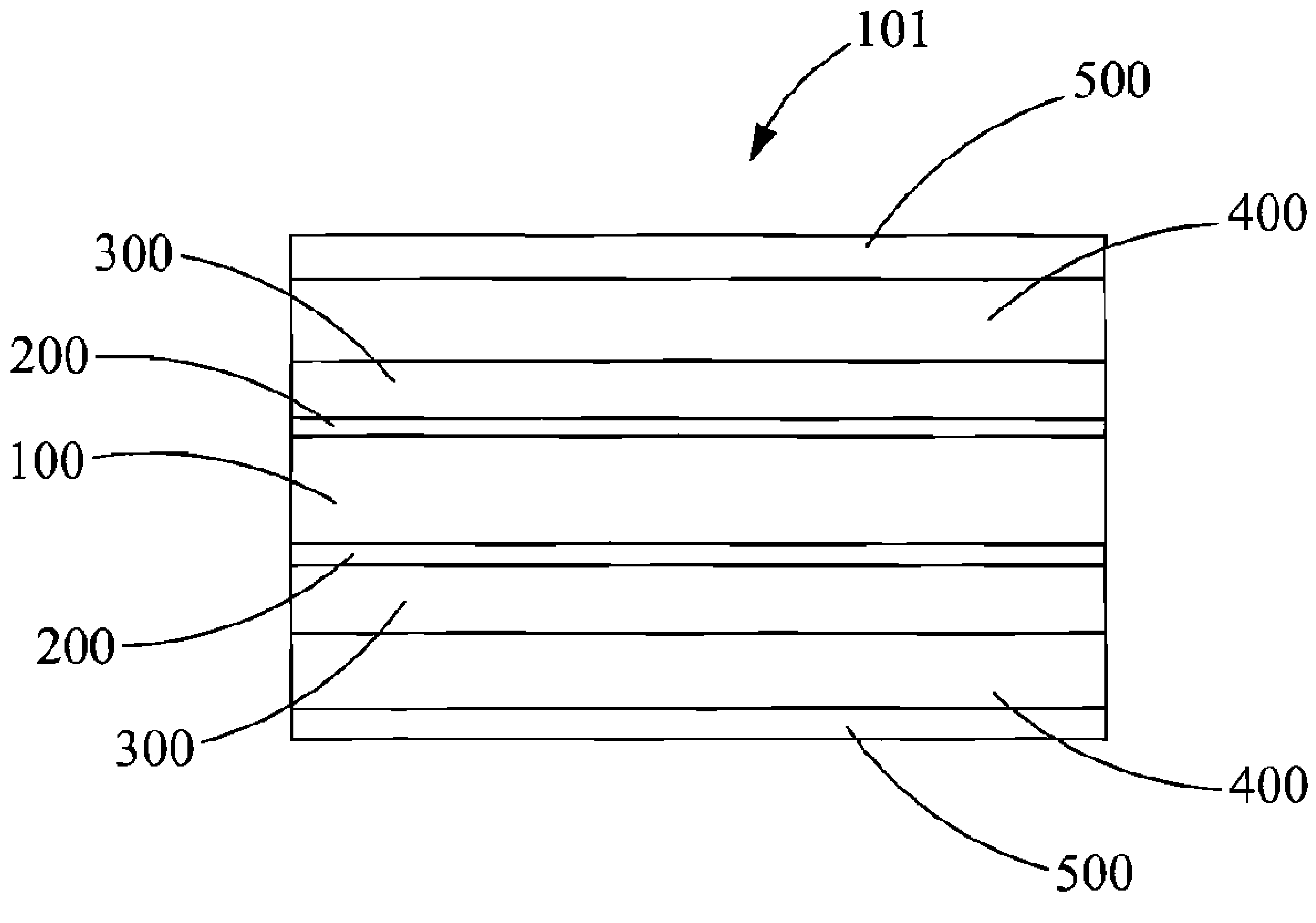

Fig. 8B

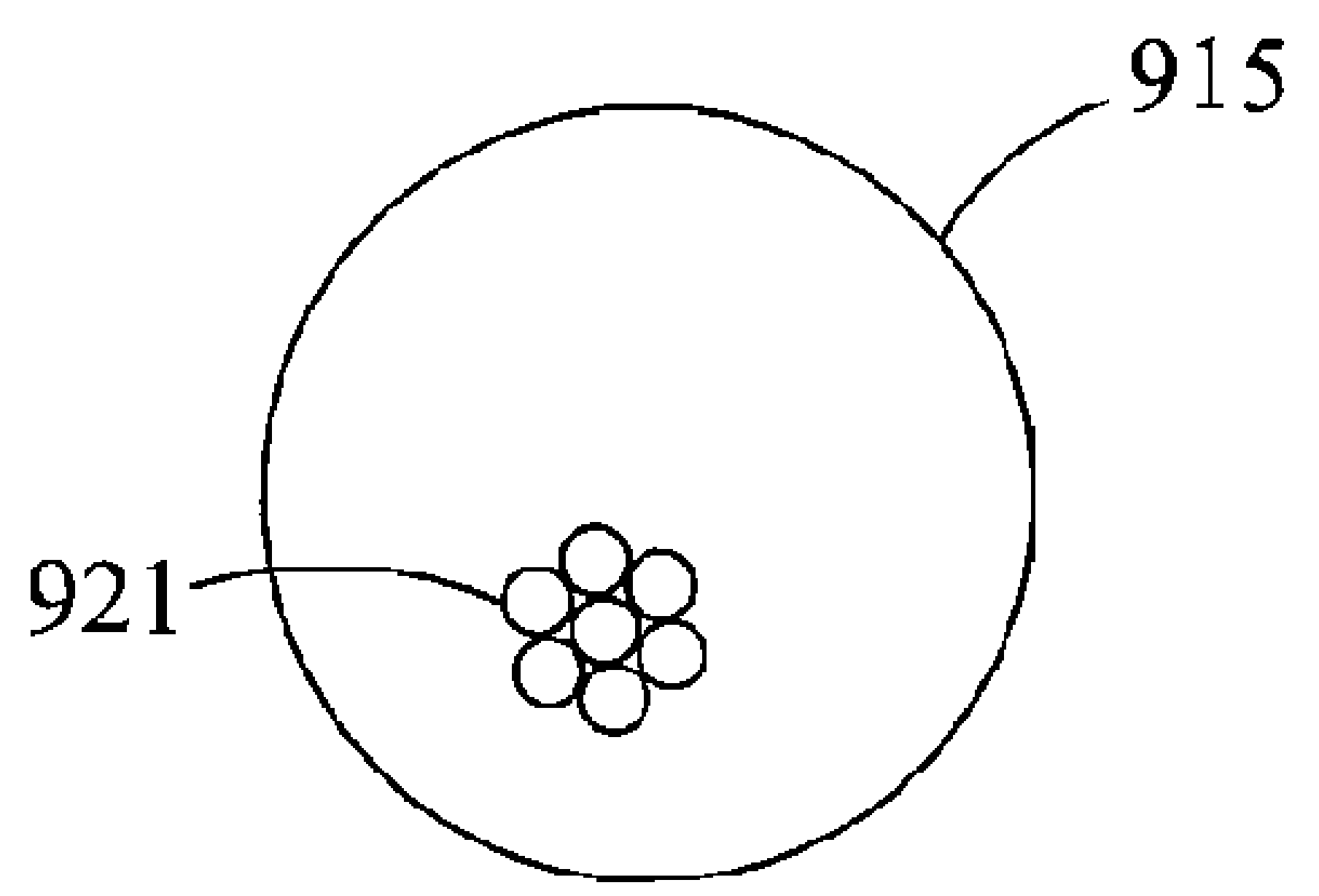

Fig. 9A

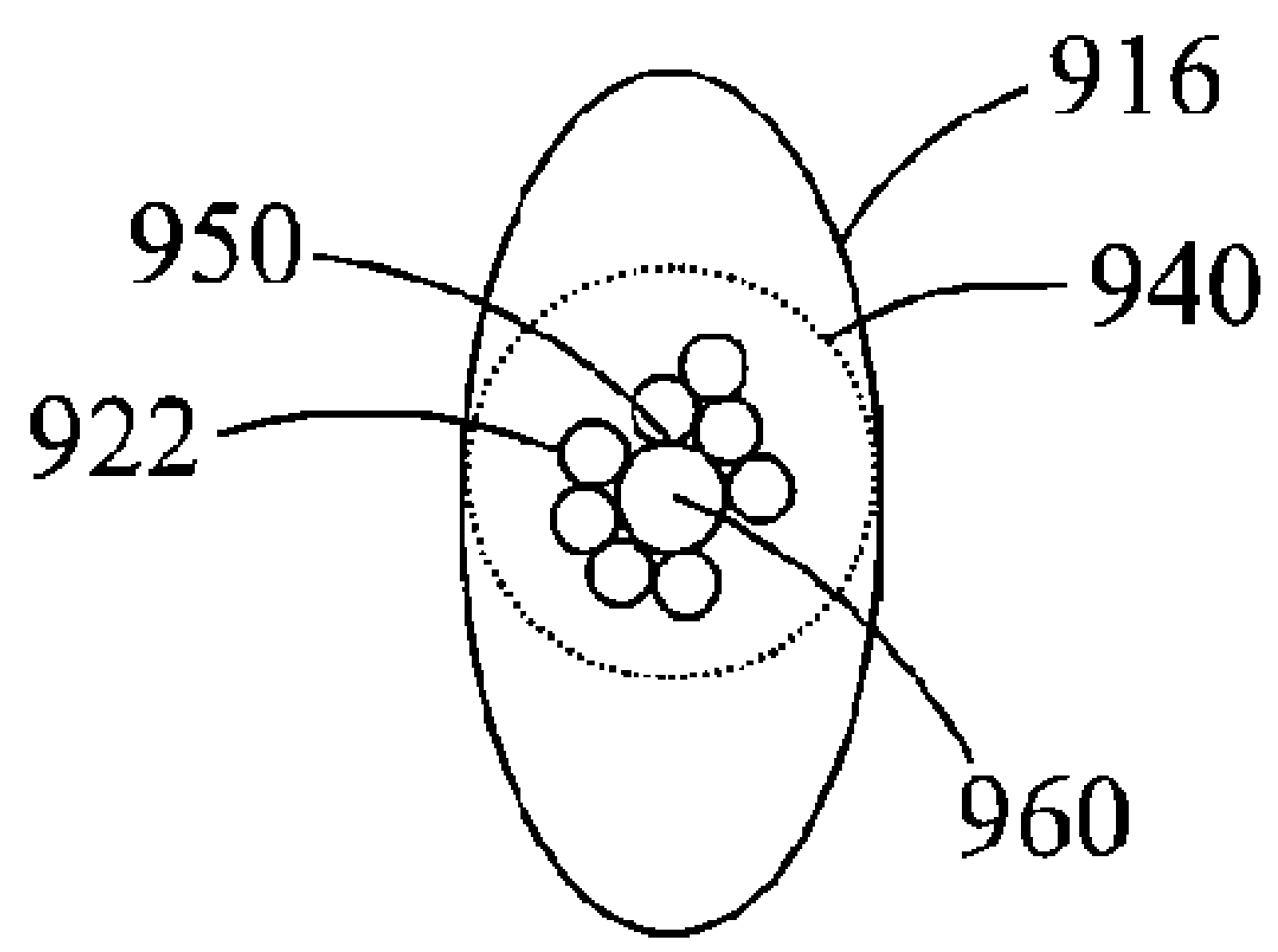

Fig. 9B

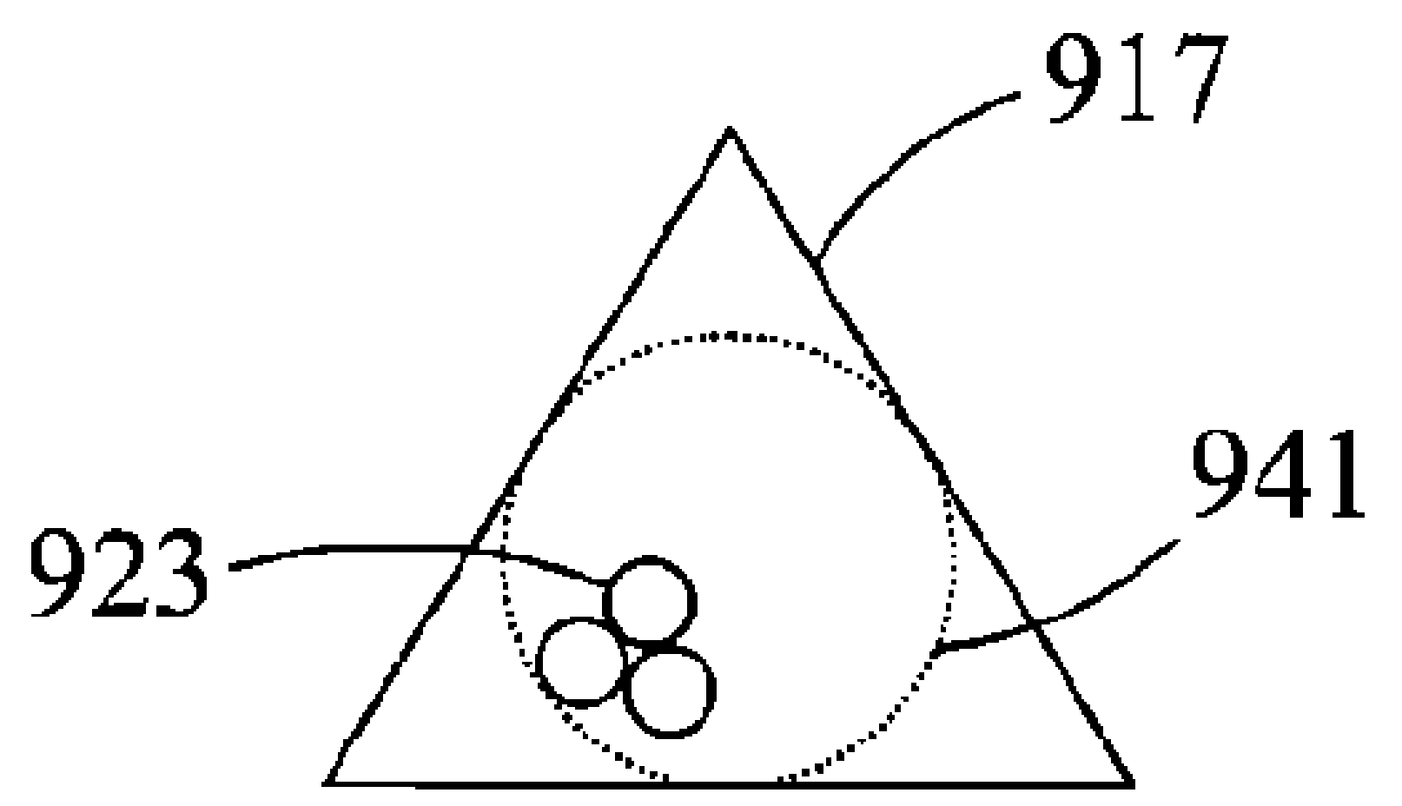

Fig. 9C

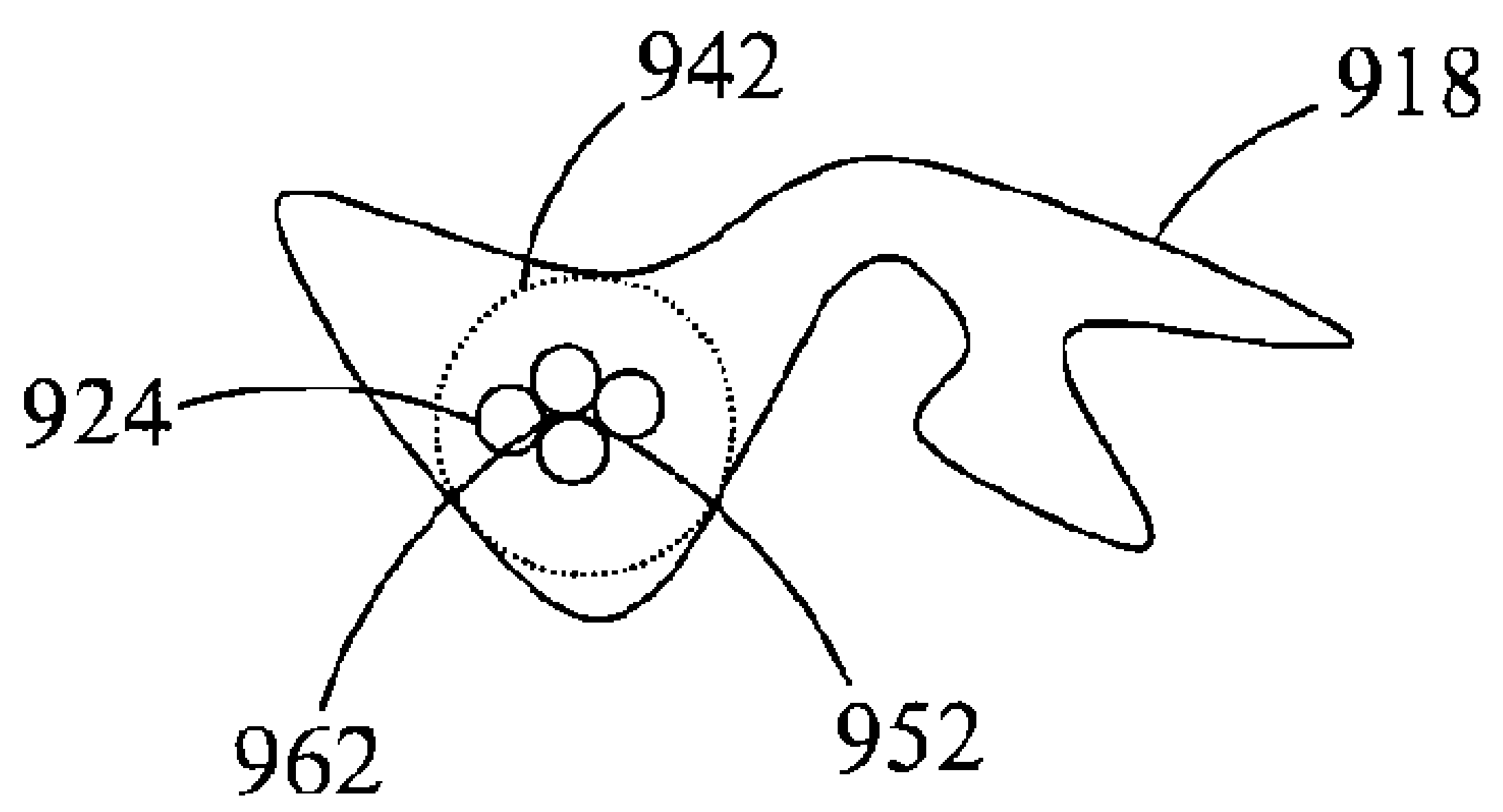

Fig. 10A

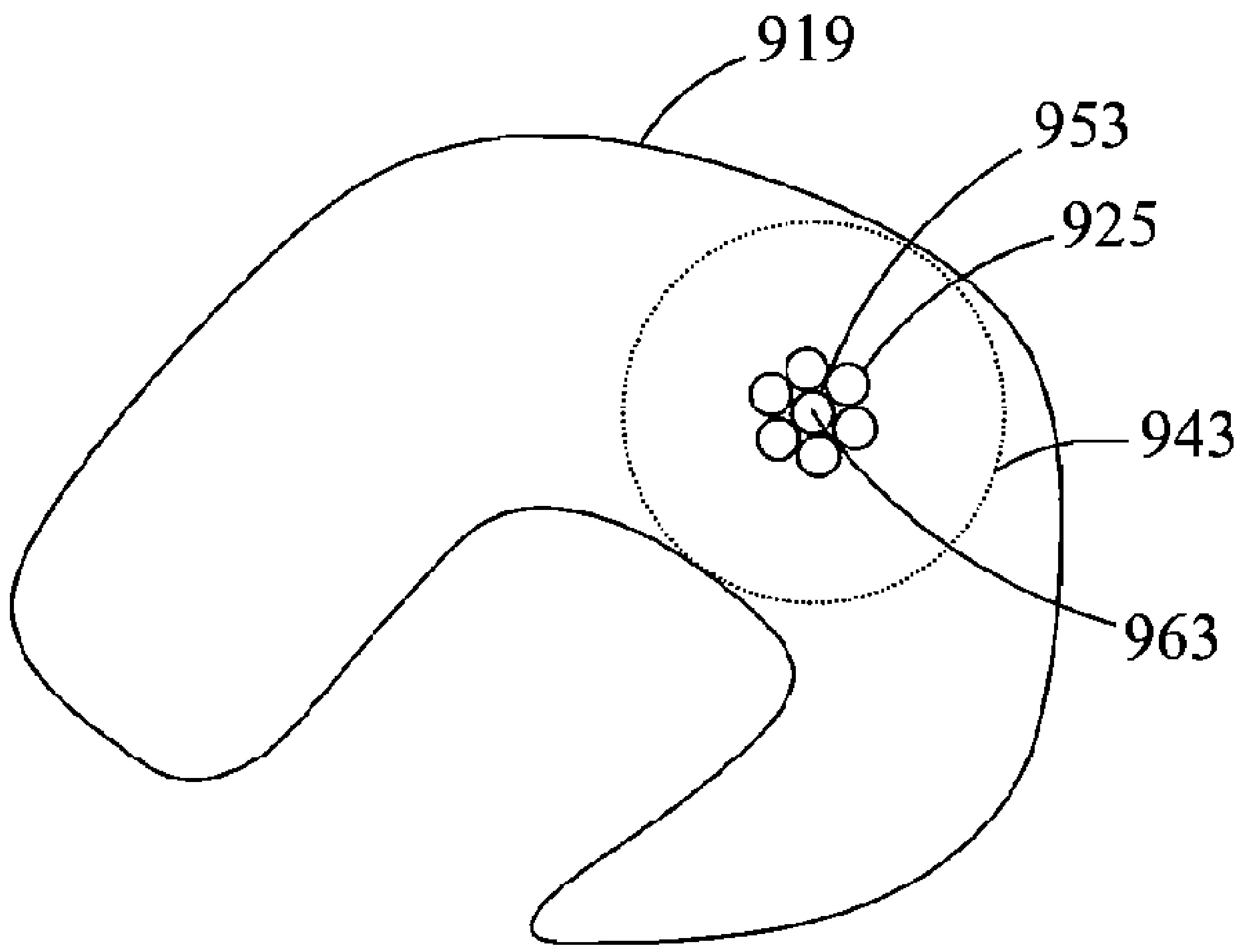

Fig. 10B

OPTICAL FIBER CONFIGURATIONS FOR TRANSMISSION OF LASER ENERGY OVER GREAT DISTANCES

This application is a continuation of patent application Ser. No. 12/840,978, filed Jul. 21, 2010, which is incorporated by reference in its entirety.

This invention was made with Government support under Award DE-AR0000044 awarded by the Office of ARPA-E U.S. Department of Energy. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to configurations of optical fibers that provide the ability to assemble, spool and unspool, deploy or use such configurations, while maintaining the fiber's ability to transmit laser energy over distances, and in particular, over great distance and at high powers. The present invention further relates to configurations that are strengthened to withstand harsh environments, such as the environments found in a borehole, a nuclear plant, or under the sea. In particular, the present invention relates to unique and novel configurations utilizing additional fiber length to minimize bending losses while providing benefits for selected predetermined applications.

As used herein, unless specified otherwise "high power laser energy" means a laser beam having at least about 5 kW (kilowatt) of power. As used herein, unless specified otherwise "great distances" means at least about 500 m (meter). As used herein the term "substantial loss of power," "substantial power loss" and similar such phrases, mean a loss of power of more than about 3.0 dB/km (decibel/kilometer) for a selected wavelength. As used herein the term "substantial power transmission" means at least about 50% transmittance.

2. Discussion of Related Art

Until the development of the inventions set forth in patent application Ser. No. 12/706,576, filed Feb. 16, 2010, the entire disclosure of which is incorporated herein by reference, it was believed that the transmission of high power laser energy over great distances without substantial loss of power was unobtainable. As a consequence, prior to the inventions of that patent application it was further believed that there was no reason to construct, or investigate the composition of, an optical fiber, an optical fiber configuration, or an optical fiber cable for the transmission of high power laser energy over great distances.

Power loss over long distances occurs in an optical fiber from many sources including: absorption loss, and in particular absorption loss from hydroxyl ions (OH^-); Rayleigh scattering; Brillouin scattering; Raman scattering; defects; inclusions; and bending loss. These problems have been documented in the literature.

An example of the prior belief in the art that a paradigm existed between the transmission of high power laser energy over great distances and substantial power loss, is illustrated in the article by Muto et al., titled "Laser cutting for thick concrete by multi-pass technique," CHINESE OPTICS LETTERS Vol. 5, Supplement May 31, 2007, pages S39-S41 (hereinafter referred to as "Muto"). Although Muto states that 4 kW of power were delivered down a 1 km fiber, when 5 kW of laser power was put into the fiber, Muto fails to eliminate the stimulated Raman scattering ("SRS") phenomena. As shown by Muto's paper this deleterious phenomenon will effectively clamp the output power as length or power is increased. The SRS phenomenon is shown by the spectrum in FIG. 3 of Muto. Thus, prior to the invention of Ser. No. 12/706,576, it was believed that as input laser power, or the length of the fiber increased, the power output of a fiber would not increase because of the stimulated Brillouin scattering ("SBS"), SRS and other nonlinear phenomena. In particular, SBS would transfer the output power back up the fiber toward the input. Further, SBS, SRS, as well as the other deleterious nonlinear effects, in addition to limiting the amount of power that can be transmitted out of the fiber, can result in fiber heating and ultimate failure. Thus, as recognized by Muto, at page S41 "[i]t is found that 10-kW-power delivery is feasible through a 250-m-long fiber with the core diameter of 150 μam. The physical phenomenon which restricts the transmitted power is SRS." Thus, Muto, as did others before him, failed to deliver high power laser energy over great distances.

Further, Muto does not disclose, discuss or address the placing of its optical fiber in any protective tubing or material, the coiling and uncoiling of its fiber or the strengthening of its fiber for use in a particular application. In particular, Muto does not address the bending losses associated with such configurations and, in particular, the bending losses that are associated with strengthened configurations.

The present invention provides solutions to bending loss problems that are associated with configuring optical fibers in protective structures and, in particular, in placing long lengths of high power optical fibers in protective tubing and then coiling and uncoiling such a configuration. Various solutions, examples of which are provided in this specification, are provided for minimizing, and in certain instances eliminating to any practical extent, bending losses that result from such configurations.

The present invention advances the art of laser delivery, and in particular the art of high power laser delivery, by providing an optical fiber configuration that avoids or mitigates the bending losses associated with optical fiber configurations and, in particular, provides an optical fiber configuration for the transmission of high power laser energy over great distances in harsh environments without substantial power loss.

SUMMARY

It is desirable to have an optical fiber configuration that provides for the delivery of laser energy and in particular high power laser energy over great distances and without substantial power loss, in particular losses from bending. The present invention, among other things, solves these needs by providing the articles of manufacture, devices and processes taught herein.

Thus, there is provided an optical fiber configuration for transmitting laser energy over great distances for use in an application, the optical fiber configuration having an optical fiber, that has a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin}). The configuration also has an outer protective member around the optical fiber, which has a first end, a second end, and a length (L_{OPM}) defined between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F. In this configuration, the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous; the optical fiber configuration has a predetermined temperature range (ΔT), a

predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil}); and the L_F is greater than the L_{OPM}, so that L_F-L_{OPM}=AFL (additional fiber length). In this configuration the optical fiber takes a helical non-following path within the outer protective member; and, the AFL is equal to or between at least one of: an AFL[L] from Formulas 2 and 4; or an AFL[%] from Formulas 1 and 3, which formulas are set forth herein.

There is further provided an optical fiber configuration for transmitting laser energy over great distances, having an optical fiber, which has a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin}). This configuration further has an outer protective member around the optical fiber, the outer protective member has a first end, a second end, and a length (L_{OPM}) between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F. The configuration is further characterized in that the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous; wherein the optical fiber configuration has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil}); and wherein the L_F is greater than the L_{OPM}, so that L_F-L_{OPM}=AFL (additional fiber length). In this configuration the optical fiber takes on a sinusoidal non-following path within the outer protective member; and, the AFL is equal to or between at least one of: an AFL[L] from Formulas 9 and 11; or an AFL[%] from Formulas 8 and 10, set forth herein.

There is additionally provided an optical fiber configuration for transmitting laser energy over great distances for use in an application, having an optical fiber, a portion of which has a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin}). This configuration further has an outer protective member around the optical fiber portion, a portion of the outer protective member comprising a first end, a second end, and a length (L_{OPM}) defined between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F. The configuration is characterized by the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous or being coterminous, which would be include as substantially coterminous. This configuration has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil}); wherein the L_F is greater than the L_{OPM}, so that L_F-L_{OPM}=AFL (additional fiber length). It further has the optical fiber taking a helical non-following path within the outer protective member; and, the AFL is equal to or between at least one of: an AFL[L] from Formulas 2 and 4; or an AFL[%] from Formulas 1 and 3 set forth herein. This optical fiber configuration is capable of transmitting at least about 1 kW, about 2 kW, and about 10 kW of laser energy over great distances without substantial bending losses.

There is also provided an optical fiber configuration for transmitting laser energy over great distances for use in an application, having an optical fiber, a portion of the fiber comprising a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin}). The configuration further having an outer protective member around the optical fiber portion, a portion of the outer protective member comprising a first end, a second end, and a length (L_{OPM}) between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F. In this configuration the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous; wherein the optical fiber configuration has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil}); and wherein the L_F is greater than the L_{OPM}, so that L_F-L_{OPM}=AFL (additional fiber length). In this configuration the optical fiber takes a sinusoidal non-following path within the outer protective member; and the AFL is equal to or between at least one of: an AFL[L] from Formulas 9 and 11; or an AFL[%] from Formulas 8 and 10 set forth herein. This optical fiber configuration is capable of transmitting at least about 1 kW, of about 2 kW or about 10 kW of laser energy over great distances without substantial bending losses.

Additionally, there is provided an optical fiber configuration for reducing bending losses for use in an application, which has an optical fiber that has a fiber core, the fiber core having a diameter of at least about 100 μm, an outer protective member in association with the optical fiber, and a means for simultaneously providing a benefit of additional fiber length while minimizing the bending losses associated with additional fiber length. In this configuration there may further be a plurality of optical fibers and wherein the outer protective member has a substantially convex outer geometry, or a plurality of optical fibers and wherein the outer protective member has a substantially concave outer geometry. These configurations may still further be capable of transmitting laser energy greater than about 5 kW, over distances greater than about 1 km without substantial power loss and may yet still further be capable of transmitting laser energy greater than about 10 kW, over distances greater than about 1 km without substantial power loss.

In these configurations provided herein the additional fiber length benefits may be, among others, separate or combined: accommodating the coiling and uncoiling of the configuration; accommodating a difference in tensile strength between the optical fiber and the outer protective member; accommodating a difference in deformation between the optical fiber and the outer protective member; accommodating a difference in deformation between the optical fiber and the outer protective member brought about by thermal factors; holding or affixing the optical fiber within the outer protective member; providing an attachment point, or section, for attaching tools, fibers, couplers, or connectors to the optical fiber; and, reducing rattling of the optical fiber within the outer protective member.

There is also provided methods for making the optical fiber configurations provided herein, which methods include selecting a value for an inner radius of the outer protective member, R_{OPM}, selecting a value for an outer radius of the fiber, R_F. selecting a value for a temperature change that the configuration is capable of withstanding, ΔT; selecting a value for a mechanical strain that the configuration is capable of withstanding, ϵ; selecting a value for the coefficient of thermal expansion of the fiber, CTE_F; selecting a value for a coefficient of thermal expansion of the outer protective member, CTE_{OPM}; selecting a value for a length of outer protective member at ambient temperature and no mechanical strain, L_{OPM}; selecting a value for a minimum bend radius of the fiber, R_{Fmin}; selecting a value for an inner radius of a coil of the configuration, R_{coil}; selecting that the fiber will have a non-following path that may be helical, sinusoidal or combinations thereof, within the outer protective member; and, using these determined values to select a maximum AFL[L] and a minimum AFL[L] using the formulas provided herein and making the optical fiber configuration in accordance with the determined maximum and minimum AFL[L]s, such that the total fiber length is between the maximum and minimum determined AFL[L]s.

Still further there is provided an optical fiber configuration for transmitting laser energy over great distances for use in an application, the optical fiber configuration comprising: an optical fiber, the optical fiber comprising a first end, a second end, and a length (LF) defined between the first and second optical fiber ends that is greater than approximately 500 m, an outer protective member around the optical fiber, the outer protective member comprising a first end, a second end, and a length (LOPM) defined between the first and second outer protective member ends; wherein the LF is greater than the LOPM; and the optical fiber and outer protective member configured so that when high power laser energy is directed from the first optical fiber end to the second fiber end there is not substantial loss of power of the high power laser energy at the second optical fiber end when compared with initial power of the high power laser energy entering the first optical fiber end. This optical fiber configuration may further have configurations in which the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous; wherein the optical fiber takes a helical non-following path within the outer protective member; wherein the optical fiber takes a helical non-following path within the outer protective member; wherein the optical fiber takes a sinusoidal non-following path within the outer protective member; and, wherein the optical fiber takes a sinusoidal non-following path within the outer protective member.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustration of a longitudinal and end view cross section of a relaxed fiber in a protective member.

FIG. **2** is an illustration of a longitudinal view cross section of an optical fiber configuration having a non-following helical fiber path.

FIG. **3** is an illustration of a longitudinal view cross section of an optical fiber configuration having a non-following sinusoidal fiber path.

FIG. **4** is an illustration of a longitudinal view cross section of a coil of an optical fiber configuration having a non-following path.

FIG. **5** is an illustration of an end view cross section of a wireline having an optical fiber configuration.

FIG. **6** is an illustration of an end view cross section of a wireline optical fiber configuration.

FIG. **7** is an illustration of longitudinal view cross section of an optical fiber configuration having portions having varying non-following fiber paths.

FIG. **8**A is an illustration of an end view cross section of a fiber.

FIG. **8**B is an illustration of a longitudinal cross section of the fiber of FIG. **8**A.

FIGS. **9**A to C are illustrations of end view cross sections of exemplary optical fiber configurations having multiple fibers and substantially convex outer geometries.

FIGS. **10**A to B are illustrations of end view cross sections of exemplary optical fiber configurations having multiple fibers and substantially concave outer geometries.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In general, the present inventions relate to optical fiber configurations for transmitting laser energy over long distances without substantial loss of power. These inventions further relate to such configurations for transmitting high power laser energy over great distances, and in particular for doing so in harsh environments, while minimizing bending losses that may be brought on by means taken to protect the fibers in such harsh environments.

Thus, in general, and by way of illustrative examples, there are provided in FIGS. **1** to **4** illustrations of optical fiber configurations. In these figures like numbers have like meaning. Thus, there is provided an optical fiber **10** and an outer protective member **15**, e.g., a tube.

The optical fiber **10** has a fiber core and may preferably have a fiber cladding, and a coating, and may also have a protective layer or layers. The fiber cladding surrounds the fiber core, and the coating, if present, surrounds the cladding. The fiber core is preferably circular in cross section. The outer protective member **15** may be made from any suitable material necessary to meet the requirements of a particular use, based upon various requirements, such as for example temperature, pressure, length, weight and the presence of solvents, other materials, or conditions that could degrade, damage or effect the fiber's ability to transmit laser energy. The space **22** between the outer surface of the fiber and the inner surface of the protective member, may further be filled with, or otherwise contain, a gel, an elastomer or some other material, such as a fluid. The material, if any, selected for use in the space **22** may be selected, among other reasons, to reduce movement or rattling of the fiber in the protective member, to aid in the assembly of the optical fiber configuration, to protect the fiber from mechanical damage, to protect the fiber from thermal damage, to restrain the fiber in a particular configuration, to support the fiber when hanging vertically within the protective member, or other purposes.

The fiber core may preferably be composed of fused silica, which preferably has a water content of at most about 0.25 ppm. The fiber core may be composed of other materials, such as those disclosed in U.S. Patent Application Publication No. 2010/0044106, the entire disclosure of which is incorporated herein by reference. Higher purity materials, and the highest purity material available, for use in the fiber core are preferred. This higher purity material minimizes the scattering losses and absorption losses caused by defects and inclusions. The fiber core is about 200 to about 1000 μm (microns) in diameter or greater, preferably from about 500 to about 700 μm in diameter and more preferably about 600 μm in diameter. As used herein the term "about" would include ranges of plus or minus 10%.

The fiber cladding may preferably be composed of fluorine doped fused silica. The fiber cladding may be composed of other materials such as fused silica doped with index-altering ions, e.g., germanium, as well as those disclosed in U.S. Patent Application Publication No. 2010/0044106. The fiber cladding thickness, depending upon the wavelength of the laser being used and the fiber core diameter, is from about 50 μm to about 250 μm, but could also be substantially thicker, preferably about 40 μm to about 70 μm and more preferably about 60 μm. As used herein with respect to a multi-layer structure, the term "thickness" means the distance between the layer's inner diameter and its outer diameter. The thickness of the fiber cladding is dependent upon and relative to the fiber core size and the intended wavelength. In general for 1.1 μm wavelength the outer diameter of the fiber cladding should be 1.1× the outer diameter of core or greater; and, for a 1.5 μm wavelength the outer diameter of the fiber cladding should be 1.5× the outer diameter of the fiber core or greater. Single, as well as, multiple fiber cladding may be utilized. Further, the fiber may have no fiber cladding.

The coating is preferably composed of a high temperature acrylate polymer, for higher temperatures a polyimide coating is desirable. The coating may be composed of other materials, such a metal, as well as those disclosed in U.S. Patent Application Publication No. 2010/0044106. The coating thickness is preferably from about 50 μm to about 250 μm, more preferably about 40 μm to about 150 μm and more preferably about 90 μm. The coating thickness may even be thicker for extreme environments, conditions and special uses or it may be thinner for environments and uses that are less demanding. Further, a hard clad, buffer and other coatings may be used as well. The coating can be tailored to protect against specific environmental or physical risks to the fiber core and fiber cladding that may be encountered or anticipated in a specific use for the cable.

The protective layer, if present, may be a single layer or multiple layers, thus it may be a first protective layer and a second protective layer, which layers may be the same or different material, or the protective layer may be a single composite layer having different materials. If present, the protective layer surrounds the fiber core (if no fiber cladding and no coating are present), the fiber cladding (if no coating is present), or the coating.

The protective layer may be a thixotropic gel. In one of the preferred embodiments, this layer primarily protects the fiber from absorption loss from hydroxyl ions as a result of hydrogen migration and protects the fiber from vibration. The thixotropic gel protects the fiber from mechanical damage due to vibrations, as well as, provides support for the fiber when hanging vertically because its viscosity increases when it is static. A palladium additive may be added to the thixotropic gel to provide hydrogen scavenging. The hydrogen that diffuses into the fiber may be problematic for germanium or similar ion doped fiber cores. When using a pure silica doped fiber core, it is less of an effect. The protective layer(s) may be composed of other materials, such as those disclosed in U.S. Patent Application Publication No. 2010/0044106. The thickness of the protective layer(s) should be selected based upon the environment and conditions of use, as well as, the desired flexibility or stiffness of the cable. Thus, the composition and thickness of the protective layer(s) can be tailored to protect against specific environmental or physical risks to the fiber core, fiber cladding and coating that may be encountered or anticipated in a specific application for the cable. Further, the use of the thixotropic gel provides the dual benefit of adding in the manufacture of the cable, as well as, providing mechanical protection to the fiber core once the cable manufacturing is completed.

A general illustration of an example of a fiber, having a coating and protective layers, is shown in FIGS. **8**A and **8**B. Thus, there is provided a fiber **101**, having a fiber core **100**, a fiber cladding **200**, a coating **300**, a first protective layer **400** and a second protective layer **500**. The fiber **101** and the fiber core **100** are preferably cylindrical in shape, while the fiber cladding **200**, coating **300** and protective layers **400** and **500** are preferably annular in shape.

The outer protective member may preferably be a stainless steel tube composed of 316 stainless steel. If a coating, or a coating and a protective layer, are used with the fiber, the outer protective member would surround those structures. Further, if multiple protective layers are used the outer protective member could constitute one of those layers.

The outer protective member, for example the outer protective member **15** shown in FIGS. **1** to **4**, may provide physical strength to the fiber over great distances, as well as, protection from physical damage and the environment in which the fiber may be used. In addition to metal, the outer protective member may be composed of composite structures, such as, for example, carbon fiber composite tubes. The outer protective member may be composed of other materials, such as those disclosed in U.S. Patent Application Publication No. 2010/0044106. The outer protective member thickness should be selected based upon the requirements for use and the environment in which the configuration may be used. The thickness may further depend upon the weight and strength of the material from which it is made. Thus, the thickness and composition of the outer protective member can be tailored to protect against specific environmental or physical risks to the fiber core, fiber cladding and coating that may be encountered or anticipated in a specific use for the configuration.

Further the outer protective member may be any shape, composition or structure that is suitable or desirable for a particular intended application or use. Thus, for example the outer protective member may be circular, elliptical, rectangular, square or combinations of these shapes, such as, a rectangle having rounded corners, as is seen for example in the tubing manufactured by Canadian Company CJS and sold under the trademark FLATpak™. For example, in FIGS. **9**A to C there is shown outer protective members **915**, **916** and **917** having substantially convex outer geometries. Thus, protective member **915** has a circular outer geometry, protective member **916** has an elliptical outer geometry and protective member **917** has a triangular outer geometry. In FIGS. **10**A and B there is further shown extreme examples, for illustrative purposes, of outer protective members **918** and **919** having substantially concave outer geometries. Further, the outer protective member does not necessarily have to be composed of a single tube or member. Thus, for example the outer protective member may be a composite of materials, such as wound wires or cables, with or without a binding media, as may be seen in the outer structure of wireline used in the oil and drilling industries. Moreover, the outer protective member need not be solid, thus a mesh, wire, or coiled structure could be employed. Further, the fiber may be packaged in a Teflon® sleeve or equivalent as another means of providing a protective member.

Turning to the configurations illustrated in FIGS. **1** to **4** the outer protective member **15** has a total length L_{18} and the optical fiber **10** has a total length L_{19}. The outer protective member has a width, which in the case of a circular tube, is its diameter, and has an inner width or diameter D_{21}. The optical fiber has an outer width or outer diameter D_{20}. The outer protective member **15** has a first end **16** and a second end **17**. The optical fiber has a first end **14** and a second end **13**. In a relaxed state shown in FIG. **1**, i.e., for practical purposes no forces restraining or affixing the fiber to the protective member, the fiber ends **14**, **13** extend beyond the outer protective member ends **16**, **17**, and thus, fiber section **12** and fiber section **11** extend beyond ends **16**, **17** of the outer protective member **15** by lengths L_{12} and L_{11}. This additional length of fiber (L_{12}, L_{11}), which in this example of a relaxed state extends beyond the ends of the outer protective member, is the additional fiber length ("AFL") that is present in the configuration, i.e., the difference in total length between the length L_{18} of the outer protective member and the total length L_{19} of the fiber (i.e., $AFL=L_{11}+L_{12}=L_{19}-L_{18}$).

In the optical fiber configurations of the present inventions, as shown by way of example in FIGS. **2** to **4**, the additional fiber length, when the fiber and protective member ends are coterminous, or substantially coterminous, is taken up and contained within the outer protective member **15** by the fiber **10** having a non-linear, or non-following, path within the outer protective member **15**. The terms "non-liner fiber path" and "non-following fiber path," as used herein, are synonymous and mean that the fiber has additional or different curves, bends or sections than the outer protective member. Examples of configurations where the fiber takes a non-following path with respect to the outer protective member **15** are shown in FIGS. **2**, **3** and **4**.

In FIG. **2** there is provided a fiber **10** in which the AFL is taken up by a helical positioning **30** of the fiber within the outer protective member **15**. In this figure there is illustrated the fiber ends **14**, **13** being coterminous with the outer protective member ends **16**, **17** respectively. The AFL is this figure would be illustrated by the difference between the total fiber length L_{19} and the total outer protective member length L_{18}. There is further shown the inner diameter D_{21} of the outer protective member **15** and the outer diameter D_{20} of the fiber **10**.

In FIG. **3** there is provided a fiber **10** in which the AFL is taken up by a sinusoidal positioning **31** of the fiber within the outer protective member **15**. In this figure there is illustrated the fiber ends **14**, **13** being substantially coterminous with the outer protective member ends **16**, **17** respectively. The AFL is this figure would be illustrated by the difference between the total fiber length L_{19} and the total outer protective member length L_{18}. Substantially coterminous would include small sections of fiber that extend, temporarily or permanently, from one or both ends of the outer protective member **15** that, for example, could be used to attach to a tool, connector, coupler, or other fiber. Substantially coterminous, in keeping with the spirit of the present invention, is meant to include optical fiber configurations, having fibers extending beyond the ends of the outer protective member in an unrelaxed state, but which obtain the benefits of having AFL, while reducing or eliminating bending losses that prior to the present invention would have been brought on by the presence of such AFL. There is further shown in FIG. **3** the inner diameter D_{21} of the outer protective member **15** and the outer diameter D_{20} of the fiber **10**.

The length indicator bars, L and D, as well as other features shown in the figures are for illustrative and qualitative purposes, and are not quantitative or drawn to scale.

In FIG. **4** these is show an optical fiber configuration **41**, for example, as if it were coiled around a spool. The configuration has a fiber **10** that has a non-following fiber path **40**, through the outer protective member **15**.

There are several benefits and needs for having additional fiber length in an optical fiber configuration. For example, the additional fiber length can accommodate differences in the thermal rates of expansion between the fiber and the outer protective member. Further, by way of example, the additional fiber length can accommodate the differences in length between the fiber and the outer protective member when the configuration is coiled, e.g., spooled, and uncoiled, e.g., deployed. Moreover, by way of example, the additional fiber length can accommodate the differences in tensile strength and deformation between the fiber and the outer protective member when the configuration is placed under load, i.e., mechanical strain. Additionally, by way of example, the additional fiber length can, to a greater or lesser extent, fix or hold the fiber in place within the outer protective member, and thus, prevent or restrict the fiber from rattling or vibrating within the outer protective member. The additional fiber length may also be partly pulled out of the protective member for attaching tools, fibers, etc., to the end of the fiber, and then, pushed back into the member for protection. As the present inventions becomes known to those of skill in the art, additional benefits and uses may be discovered, and such new uses for the present invention form a part of the scope of protection sough herein. These, as well as other, benefits and needs for additional fiber length, in particular for high power long distance optical fiber configurations, can, as illustrated herein, be determined, selected and specified for a particular application, use, environment or deployment.

However, the presence of additional fiber length in an optical fiber configuration, when the ends of the fiber and outer protective member are coterminous or substantially conterminous, may have deleterious effects on the ability to transmit laser energy. Similarly, the presence of a non-following fiber path, whether or not resultant from the presence of additional fiber length, in the optical fiber configuration, may have deleterious effects on the ability to transmit laser energy. In particular as laser power increases and the length of the configuration increases the deleterious effects of the necessary additional fiber length may range from severe, i.e., substantial power loss, to total power loss, i.e., no laser power is transmitted through the fiber. These deleterious effects are caused by bending losses that occur when the fiber takes a non-following path within the outer protective member or when the fiber is coiled too tightly.

The present inventions address and provide solutions to the problems of bending losses in optical fiber configurations caused by additional fiber length, and in particular provide solutions to the problems of bending losses in fibers having laser power greater than 1 kW, fibers having high laser power, i.e., 5 kW and greater, and in optical fiber configurations of great lengths, i.e., greater than 500 m, while at the same time providing the benefits of and meeting the needs for additional fiber length. Thus, the additional fiber length for a given fiber in a given outer protective member should be long enough to address the needs for the additional fiber length in a particular use environment and to obtain any benefits from the presence of the additional fiber length for such use in such environment, while not being so long as to give rise to excess bending losses.

Thus, the following factors as applied to the novel aspects of the present invention provide optical fiber configurations that have the requisite additional fiber length while minimizing or preventing bending losses in that configuration from the additional fiber length taking a non-following path. Predetermined values for these factors would be selected or determined for a particular application, use, environment or deployment. These factors are defined as follows:

Inner radius of the outer protective member=R_{OPM} [L] where [L] is a unit of length, such as meters.

Outer radius of the optical fiber (including cladding and coating, if present)=R_F [L].

Temperature change, i.e., temperature range, that the configuration must sustain in the intend use=ΔT [T], where [T] is a unit of temperature, such as degrees centigrade. ΔT is the difference between the average temperature along the length of the configuration that the configuration will reach during an intended use, ($AvgTL_{in\ use}$) and the average temperature along the length of the configuration that the configuration will reach when AFL is determined, e.g., when the optical fiber is assembled into the outer protective member ($\text{AvgTL}_{when\ determined}$). Thus, $\Delta T=\text{AvgTL}_{in\ use}-\text{AvgTL}_{when\ determined}$.

Mechanical strain that the configuration must sustain in the intend use=ϵ.

Coefficient of thermal expansion of the fiber=CTE_F [1/T].

Coefficient of thermal expansion of the outer protective member=CTE_{OPM}[1/T].

Length of outer protective member at ambient temperature and no mechanical strain=L_{OPM} [L].

Minimum bend radius of fiber=R_{Fmin} [L], where the minimum bend radius is that point at which the macro bending losses exceed the desired dB/km loss for a selected wavelength.

Inner radius of a coil of the configuration=R_{coil} [L].

The presently preferred embodiment of this invention, and the area where it is presently believed substantial benefits will be obtained, is in the area of configurations having greater lengths, and in particular, configurations having lengths of about 1 km or greater, between about 1 km and 2 km, from about 5 km to about 7 km and greater. To transport, store, use and deploy these long configurations they will need to be coiled, for example on a spool or creel. However, if the configuration were used in an application or location where coiling was not necessary, or otherwise contraindicated, the value for R_{coil} [L] for an uncoiled, i.e., essentially straight configuration, would be infinity.

The following ranges, teachings, relationships and examples are illustrative of the considerations that may be used in selecting or determining values for these factors. Thus, the size of the inner radius of the outer protective member, R_{OPM}, can be based, in part, upon the flexibility of the optical fiber and upon the outer diameter of the optical fiber. By way of example, the inner radius of the outer protective member can range from microns to 2.5 mm, to 4 mm and larger; for an optical fiber having a 50 μm outer diameter the inner radius of the outer protective member can range from about 125 μm to much larger; and, for an optical fiber having a 300 μm outer diameter the inner radius of the outer protective member can range from about 600 μm to about 2.5 mm to 4 mm and larger. The outer radius of the fiber, R_F, can range from about 50 μm to 4 mm or greater. The temperature change, ΔT, can range from about −273° C. to about 800° C. Higher temperature ranges are possible as higher temperature coatings are developed. The mechanical strain, ϵ, can range from about 0 to about 0.33 of the proof test strength for long term stresses, which for example is 30-40 ksi for a 20 year life time, for shorter time scale applications high stresses could be utilized. Further, compressible outer protective member may be used that could experience compressive mechanical stain and thus in this example the mechanical strain would be negative.

For a helical non-following path, such as shown in FIG. **2**, the calculations of Formulas 1 to 4 set forth below can be used to determine the range of excess fiber length available without creating adverse bending losses. Formulas 1 and 2 provide a determination of the maximum AFL as a percentage of total length of the configuration and as a length.

Formula 1

$$AFL[\%] \leq \text{mimimum of}\left[\sqrt{\frac{1}{\frac{1}{\left(\frac{1}{R_{Fmin}}-\frac{1}{R_{coil}}\right)(R_{OPM}-R_F)}-1}+1}-1 \text{ or } \sqrt{\frac{1}{\frac{1}{\left(\frac{1}{R_{Fmin}}-\frac{1}{R_{coil}}\right)(R_{OPM}-R_F)}-1}+1}-1+(CTE_{OPM}-CTE_F)\Delta T+\varepsilon\right]$$

$$AFL[L] \leq AFL[\%] \times L_{OPM}$$ Formula 2

Formulas 3 and 4 below provide a determination of the minimum AFL as a percentage of total length of the configuration and as a length.

$$AFL[\%] \geq \max[(CFT_{OPM}-CTE_F)\Delta T+\varepsilon \text{ or } 0]$$ Formula 3

$$AFL[L] \geq AFL[\%] \geq \times L_{OPM}$$ Formula 4

Accordingly, examples of optical fiber configurations of the present invention are configurations of a fiber and outer protective member wherein the AFL[L] of the fiber is between about the lengths obtained from Formulas 2 and 4, or the percentages obtained from Formulas 1 and 3, based upon predetermined selected factors for that use.

For a sinusoidal non-following path, such as shown, the calculations of Formulas 5 to 11 set forth below can be used to determine the range of excess fiber length available without creating adverse bending losses.

Formula 5

$$(\text{amplitude of sinusoid} = a)$$

$$a = R_{OPM} - R_F$$

Formula 6

$$(\text{maximum frequency of sinusoid})$$

$$b = \frac{1}{\sqrt{a \times \frac{1}{\frac{1}{R_{Fmin}}+\frac{1}{R_{coil}}}}}$$

Formula 7

$$(\text{arc length of sine curve})$$

$$F = \int_0^{L_{OPM}} \sqrt{(1+a^2b^2\cos^2 bx)}\,dx$$

Formulas 8 and 9 provide a determination of the maximum AFL as a percentage of total length of the configuration and as a length.

$$AFL[\%] \leq \text{minimum of } \left[\frac{F}{L_{OPM}} - 1 \text{ or } \frac{F}{L_{OPM}} - 1 + (CTE_{OPM} - CTE_F)\Delta T + \varepsilon\right] \quad \text{Formula 8}$$

$$AFL[L] \leq AFL[\%] \geq \times L_{OPM} \quad \text{Formula 9}$$

Formulas 10 and 11 provide a determination of the minimum AFL as a percentage of total length of the configuration and as a length, respectively.

$$AFL[\%] \geq \max[(CTE_{OPM} - CTE_F)\Delta T + \epsilon \text{ or } 0] \quad \text{Formula 10}$$

$$AFL[L] \geq AFL[\%] \times L_{OPM} \quad \text{Formula 11}$$

The relationship of the minimum bend radius as a function of numeric aperture ("NA") of the fiber can be expressed using the following factors and Formula 12. NA characterizes the range of angles over which the fiber can accept or emit light in air. Thus, the NA with respect to a point depends upon the half-angle of the maximum cone of light that can that can enter or exit the fiber, i.e., NA=n*sin(half-angle), where n is the index of refract of the medium, in this case air, which is about 1 at STP (20 C, at 1 atm.).

α=(dB/km)(power loss that is selected, specified or determined for a loss application)

$$\alpha_{sys} = \frac{\alpha}{100}$$

n=index of refraction of the core.

k=2*π/λ (where λ is equal to the wavelength of the laser in meters)

θ_c=arcsin (NA) (where NA is the NA in air)

R_{Fmin} (where units are in meters)

α=radius of fiber core (meters)

$$\alpha_{sys} = -\ln\left[2\int_0^{\theta_c} \frac{1}{.95\sqrt{\frac{\pi\tan^2\theta_c}{2}}} e^{-\frac{2\tan^2\theta}{\tan^2\theta_c}} e^{-2nk(\theta_c^2-\theta^2)} e\left[-\frac{2}{c}nk\left(R_{Fmin}\theta_c^2 - R_{Fmin}\theta^2 - 2a\right)\right]^{\frac{c}{2}} d\theta\right] \quad \text{Formula 12}$$

To determine the minimum bend radius, Formula 12 may be solved for R_{Fmin}.

Accordingly, examples of optical fiber configurations of the present invention are configurations of a fiber and outer protective member wherein the AFL[L] of the fiber is between about the lengths obtained from Formulas 9 and 11, or the percentages obtained from Formulas 8 and 10, based upon predetermined selected factors for that use.

There are provided examples of an optical fiber configuration for use in powering a down hole laser tool or laser bottom hole assembly. In the following examples different units are provided for different facts, i.e., cm and m. It should be recognized that when applying the various formulas to the factors that the units should be consistent, e.g., all length scales in the same units such as in cm.

Example 1

Inner radius of the outer protective member, R_{OPM}=1.5 mm (millimeters).

Outer radius of the fiber (including coating) R_F [L]=400 μm (microns).

Temperature change that the configuration must sustain in the intend use, ΔT [T]=100° C.

Mechanical strain that configuration must sustain in the intend use, ϵ=0.0005

Coefficient of thermal expansion of the fiber, CTE_F=0.55*10^{-6} (1/C).

Coefficient of thermal expansion of the outer protective member, CTE_{OPM}=15*10^{-6} (1/C).

Length of outer protective member at ambient temperature and no mechanical strain, L_{OPM}=2 km.

Minimum bend radius of fiber, R_{Fmin}=10 cm.

Inner radius of a coil (for example of the type shown in FIG. **4**) of the configuration, R_{coil}=1.5 m.

Wherein, the AFL[L] for a helical non-following path (for example of the type shown in FIG. **2**) is from about 3.89 to about 10.4 m; the AFL[%] for a helical non-following path is from about 0.195% to about 0.517%. Wherein, the AFL[L] for a sinusoidal non-following path (for example of the type shown in FIG. **3**) is from about 3.89 to about 5.38 m; and, the AFL[%] for a sinusoidal non-following path is from about 0.195% to about 0.269%.

Example 2

Inner radius of the outer protective member, R_{OPM}=3 mm (millimeters).

Outer radius of the fiber (including coating) R_F [L]=250 μm.

Temperature change that the configuration must sustain in the intend use, ΔT [T]=10° C.

Mechanical strain that configuration must sustain in the intend use, ϵ=0.0001.

Coefficient of thermal expansion of the fiber, CTE_F=0.55*10^{-6} (1/C).

Coefficient of thermal expansion of the outer protective member, CTE_{OPM}=15*10^{-6} (1/C).

Length of outer protective member at ambient temperature and no mechanical strain, L_{OPM}=1 km.

Minimum bend radius of fiber, R_{Fmin}=20 cm.

Inner radius of a coil (for example of the type shown in FIG. **4**) of the configuration, R_{coil}=1 m.

Wherein, the AFL[L] for a helical non-following path (for example of the type shown in FIG. **2**) is from about 0.245 to about 5.55 m; the AFL[%] for a helical non-following path is from about 0.0245% to about 0.555%. Wherein, the AFL[L] for a sinusoidal non-following path (for example of the type shown in FIG. **3**) is from about 0.245 to about 3.45 m; and, the AFL[%] for a sinusoidal non-following path is from about 0.0245% to about 0.345%.

Example 3

Inner radius of the outer protective member, R_{OPM}=1.6 mm (millimeters).

Outer radius of the fiber (including coating) R_F [L]=100 μm.

Temperature change that the configuration must sustain in the intend use, ΔT [T]=50° C.

Mechanical strain that configuration must sustain in the intend use, ϵ=0.0002.

Coefficient of thermal expansion of the fiber, $CTE_F=0.55*10^{-6}$ (1/C).

Coefficient of thermal expansion of the outer protective member, $CTE_{OPM}=26*10^{-6}$ (1/C).

Length of outer protective member at ambient temperature and no mechanical strain, $L_{OPM}=3$ km.

Minimum bend radius of fiber, $R_{Fmin}=10$ cm.

Inner radius of a coil of the configuration, $R_{coil}=50$ cm.

Wherein, the AFL[L] for a helical non-following path (for example of the type in FIG. **2**) is from about 4.42 to about 18.2 m; the AFL[%] for a helical non-following path is from about 0.147% to about 0.61%. Wherein, the AFL[L] for a sinusoidal non-following path (for example of the type shown in FIG. **3**) is from about 4.42 to about 11.4 m; and, the AFL[%] for a sinusoidal non-following path is from about 0.147% to about 0.3792%.

Example 4

Inner radius of the outer protective member, $R_{OPM}=10$ mm (millimeters).

Outer radius of the fiber (including coating) R_F [L]=300 μm.

Temperature change that the configuration must sustain in the intend use, ΔT [T]=0° C.

Mechanical strain that configuration must sustain in the intend use, $\epsilon=0$.

Coefficient of thermal expansion of the fiber, $CTE_F=0.55*10^{-6}$ (1/C).

Coefficient of thermal expansion of the outer protective member, $CTE_{OPM}=15*10^{-6}$ (1/C).

Length of outer protective member at ambient temperature and no mechanical strain, $L_{OPM}=0.5$ km.

Minimum bend radius of fiber, $R_{Fmin}=25$ cm.

Inner radius of a coil of the configuration, R_{coil}=Infinity. Thus, in this example the configuration would not be coiled during use, and would be kept substantially straight during use.

Wherein, the AFL[L] for a helical non-following path (for example of the type shown in FIG. **2**) is from about 0 to about 10 m; the AFL[%] for a helical non-following path is from about 0% to about 2%. Wherein, the AFL[L] for a sinusoidal non-following path (for example of the type shown in FIG. **3**) is from about 0 to about 4.88 m; and, the AFL[%] for a sinusoidal non-following path is from about 0% to about 0.976%.

The optical fiber configurations can be greater than about 0.5 km (kilometer), greater than about 1 km, greater than about 2 km, greater than about 3 km, greater than about 4 km and greater than about 5 km and between 1 km and 5 km and between 1 km and 20 km. As used herein the length of the configuration refers to the length when the fiber end and the outer protective end are substantially coterminous. In general the preferred fibers using the preferred optical fiber configurations can withstand temperatures of up to about 200° C. to about 300° C., pressures of up to about 3000 psi and as great as 36,000 psi, and corrosive environments over the length of the fiber without substantial loss of power and for extended periods of time. However, higher temperatures, as well as very low temperatures, greater pressures and harsher environments are contemplated and within the scope of the present inventions. The optical fiber can have a power loss, for a given wavelength, of less then about 3.0 dB/km, less than about 2.0 dB/km, less than about 1.5 dB/km, less than about 1.0 dB/km, less than about 0.5 dB/km and less than about 0.3 dB/km. The optical fiber configurations can have power transmissions of at least about 50%, at least about 60%, at least about 80%, and at least about 90%.

Any type of high power laser may be used as a source of laser energy for use with the optical fiber configurations of the present invention. Examples of such lasers are disclosed in U.S. Patent Application Publication No. 2010/0044106, the disclosure of which is incorporated herein by reference. High power infrared lasers are preferable. Wavelengths of about 1490 nm, about 1550 nm, and about 1080 nm have even greater potential benefits. Further, broadband beams within these wavelength ranges may have greater benefits. Preferably, the laser should generate a laser beam in the infrared wavelength having a power of at least about 1 kW, at least about 3 kW, at least about 5 kW, at least about 10 kW, and at least about 20 kW or greater. An example of such a preferred laser for use with the optical fiber configurations of the present invention is ytterbium fiber laser such as the IPG YLR-20000. The detailed properties of this laser are disclosed in U.S. Patent Application Publication No. 2010/0044106. The preferred laser includes 20 modules. The gain bandwidth of a fiber laser is on the order of 20 nm, the linewidth of the free oscillator is 3 nm, Full Width Half Maximum (FWHM) may range from 3 nm to 5 nm (although higher linewidths including 10 nm are envisioned and contemplated). Each module's wavelength is slightly different. The modules further each create a multi-mode beam. Thus, the cumulative effect of combining the beams from the modules is to maintain the Raman gain and the Brillouin gain at a lower value corresponding to the wavelengths and linewidths of the individual modules, and thus, consequently reducing the SBS and SRS phenomenon in the fiber when the combined beams are transmitted through the fiber.

FIG. **5** illustrates a wireline **50** having two layers of helically wound armor wires, an outer layer **51** and an inner layer **52**. Other types and arrangement of wirelines are know to those of skill in the art. There is further provided a plurality of insulated electrical conductors **53** and an optical fiber configuration **54**, the configuration **54** having an optical fiber **55** and an outer protective member **56**. The space **58** between the outer surface of the fiber and the inner surface of the protective member, may further be filled with, or otherwise contain, a gel, an elastomer or some other material, such as a fluid. Similarly, a second space **59** may further be filled with, or otherwise contain, a gel, an elastomer or some other material, such as a fluid, which material will prevent the armor wires from crushing inwardly from external pressure of an application, such as the pressure found in a well bore. Further the fiber may be packaged in a Teflon® sleeve or equivalent type of material or sleeve.

FIG. **6** illustrates a wireline **60** having outer armor wire layer **61** and inner armor wire layer **62**. The wireline **60** constitutes an optical fiber configuration having a fiber **65** and an outer protective member **66**. The space **69** between the fiber **65** and the armor wire layer **62** may further be filled with, or otherwise contain, a gel, an elastomer or some other material, such as a fluid, which material will prevent the armor wires from crushing inwardly from external pressure of an application, such as the pressure found in a well bore.

As used herein the term line structure should be given its broadest construction, unless specifically stated otherwise, and would include without limitation, wireline, coiled tubing, logging cable, cable structures used for completion, workover, drilling, seismic, sensing logging and subsea completion and other subsea activities, scale removal, wax removal, pipe cleaning, casing cleaning, cleaning of other tubulars, cables used for ROV control power and data transmission, lines structures made from steal, wire and composite materials such as carbon fiber, wire and mesh, line structures used for monitoring and evaluating pipeline and boreholes, and would include without limitation such structures as Power & Data Composite Coiled Tubing (PDT-COIL) and structures such as Smart Pipe®. The optical fiber configurations can be used in conjunction with, in association with, or as part of a line structure.

FIG. **7** illustrates an optical fiber configuration **70** having a fiber **74**, an outer protective member **75** and portions **72** of the fiber each portion having a length and differing fiber paths, **72***a*, **72***b*, **72***c*, and **72***d*. Fiber paths **72***a*, **72***b* and **72***d* are non-following paths, while path **72***c* is a following path. Path **72***a* is a helical type of non-following path. Paths **72***b* and **72***d* are sinusoidal types of non-following paths. The optical fiber configuration **70** has ends **76**, wherein it shown that the fiber is conterminous with the outer protective member. The fibers in these sections may have different or the same diameters.

Example 5

In this example the fiber is of the type shown in FIG. **7**, having a first section having a helical non-following fiber path, a second section having following fiber path, and a third section having a sinusoidal non-following fiber path. The entire configuration and its section would have the following values, factors and AFLs, which are set out in Table I.

member, R_{OPM}, and the outer radius of the fiber, R_F. Thus, for multi-fiber configurations and configurations where the outer protective member is not essentially circular, the R_{OPM} will be the minimum distance from a member of the fiber bundle to the outer protective member, when the moment of inertia of the bundle is located at the center of the largest circle that can be inscribed within the outer protective member, plus the radius of the smallest diameter fiber in the bundle. The R_F is the radius of the smallest diameter fiber in the bundle.

For the example of FIG. **9**A the largest circle that can be inscribed would be the inner diameter of the outer protective member **915**, i.e., the largest circle would be concentric with the inner diameter of the outer protective member **915**.

By way of illustration the R_{OPM} for the configuration of FIG. **9**B would be determined as follows. The largest circle **940** that can be inscribed within the internal diameter of the outer protective member **916** is determined. The center **950** of the largest circle **940** is determined. The moment of inertia **960** of the bundle **922** is determined. The fiber bundle **922** and the largest circle **940** are then for computational purposes centered by aligning the circle center **950** and the moment of inertia **960**. The R_{OPM} is then equal to the smallest distance between the computationally centered fiber bundle (i.e., when moment **960** and center **950** are aligned) and the outer protective member **916**, plus the radius of the smallest diameter fiber in the bundle.

TABLE I

Factor	First Section	Second Section	Third Section	Total
Fiber Path type	helical	following	sinusoidal	n/a
Section length	1.5 km	0.1 km	0.4 km	2 km
R_{OPM}	2 mm	2 mm	2 mm	n/a
R_F	600 μm	600 μm	600 μm	n/a
ΔT	100° C.	100° C.	50° C.	n/a
ϵ	0.0005	0.0005	0.0005	n/a
CTE_F	$0.55 * 10^{-6}$ (1/C).	$0.55 * 10^{-6}$ (1/C).	$0.55 * 10^{-6}$ (1/C).	n/a
CTE_{OPM}	$15 * 10^{-6}$ (1/C).	$15 * 10^{-6}$ (1/C).	$15 * 10^{-6}$ (1/C).	n/a
L_{OPM}	1.5 km	0.1 km	0.4 km	2 km
R_{Fmin}	10 cm	10 cm	10 cm	n/a
R_{coil}	1 m	1 m	1 m	1 m
AFL [L]	2.92 to 9.54 m	.05 to .1 m	.788 to 1.41 m	3.758 to 11.05 m
AFL [%]	.1945% to .636%	.05% to .1%	.1945% to .353%	.188% to .553%

n/a means not applicable.

Note:

in this example the third section of the configuration would be intended to remain near the top of the borehole and not be subjected to as large a ΔT as the lower sections (i.e., the first and second sections).

The entire configuration, i.e., all three section are wound on the same spool to form a coil.

The total AFL[L] and AFL [%] are the sums of the individual AFLs for each section.

In FIGS. **9**A to **9**C there is shown optical fiber configurations having outer protective members **915**, **916** and **917** having substantially convex outer geometries. Thus, protective member **915** has a circular outer geometry, protective member **916** has an elliptical outer geometry and protective member **917** has a triangular outer geometry. Moreover these configurations of FIGS. **9**A to **9**C have fiber bundles **921**, **922** and **923**, which bundles have multiple fibers. Further, bundle **922** has fibers of different diameters. In FIGS. **10**A and **10**B there is further shown optical fiber configurations having extreme examples, for illustrative purposes, of outer protective members **918** and **919** having substantially concave outer geometries. These configurations of FIGS. **10**A and **10**B have fiber bundles **924** and **925**. The fibers in these bundles may also be of different diameters.

The forgoing formulas 1 to 12 can be used to determine AFL, for the types of configurations shown in FIGS. **9**A-C and **10**A-B, with the following modification to the definitions of the factors for the inner radius of the outer protective

By way of illustration the R_{OPM} for the configuration of FIG. **10**A would be determined as follows. The largest circle **942** that can be inscribed within the internal diameter of the outer protective member **918** is determined. The center **952** of the largest circle **942** is determined. The moment of inertia **962** of the bundle **924** is determined. The fiber bundle **924** and the largest circle **942** are then for computational purposes centered by aligning the circle center **952** and the moment of inertia **962**. The R_{OPM} is then equal to the smallest distance between the computationally centered fiber bundle (i.e., when moment **962** and center **952** are aligned) and the outer protective member **918** plus the radius of the smallest diameter fiber in the bundle.

Similarly, and by way of illustration the R_{OPM} for the configuration of FIG. **10**B would be determined as follows. The largest circle **943** that can be inscribed within the internal diameter of the outer protective member **919** is determined. The center **953** of the largest circle **943** is determined. The moment of inertia **963** of the bundle **925** is determined. The fiber bundle **925** and the largest circle **943** are then for computational purposes centered by aligning the circle center **953** and the moment of inertia **963**. Thus, R_{OPM} is equals to the smallest distance between the computationally centered fiber bundle (i.e., when moment **963** and center **953** are aligned) and the outer protective member **919**, plus the radius of the smallest diameter fiber in the bundle.

The invention may be embodied in other forms than those specifically disclosed herein without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive, and the scope of the invention is commensurate with the appended claims rather than the foregoing description.

What is claimed is:

1. A method of using a line structure for transmitting laser energy, the method comprising:

a. providing a line structure,

b. the line structure comprising:

i. an optical fiber comprising a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin});

ii. an outer protective member around the optical fiber, the outer protective member comprising a first end, a second end, and a length (L_{OPM}) defined between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F;

iii. the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous;

iv. the line structure has a predetermined temperature range for use (ΔT), a predetermined mechanical strain (ϵ), and when the optical fiber is wound into a coil it has a predetermined inner radius of coil (R_{coil});

v. wherein the L_F is greater than the L_{OPM}, so that L_P-L_{OPM}=AFL (additional fiber length);

vi. the optical fiber taking a helical non-following path within the outer protective member;

vii. the AFL is equal to or between at least one of: an AFL[L] from Formulas 2 and 4 as defined in Applicants' Specification; or an AFL[%] from Formulas 1 and 3 as defined in Applicants' Specification;

c. deploying the line structure;

d. transmitting laser energy through the optical fiber; and,

e. recovering the line structure.

2. The method of claim **1**, wherein the line structure is deployed down a borehole.

3. The method of claim **1**, wherein the line structure is deployed from a spool.

4. The method of claim **1**, wherein the line structure is recovered to a spool.

5. A method of transmitting laser energy over a line structure, the method comprising:

a. providing a line structure,

b. the line structure comprising:

i. an optical fiber, the fiber comprising a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin});

ii. an outer protective member around the optical fiber, the outer protective member comprising a first end, a second end, and a length (L_{OPM}) between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F;

iii. the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous;

iv. wherein the line structure has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil});

v. wherein the L_F is greater than the L_{OPM}, so that L_F-L_{OPM}=AFL (additional fiber length);

vi. the optical fiber taking a sinusoidal non-following path within the outer protective member;

vii. the AFL is equal to or between at least one of: an AFL[L] from Formulas 9 and 11 as defined in Applicants' Specification; or an AFL[%] from Formulas 8 and 10 as defined in Applicants' Specification;

c. deploying the line structure;

d. transmitting laser energy through the optical fiber; and,

e. recovering the line structure.

6. The method of claim **5**, wherein: R_{OPM} is at least about 1.0 mm; R_F is at least about 100 μm; the ΔT is at least about 50° C.; ϵ is at least about 0.01%; CTE_F is at least about $0.5*10^{-6}$ (1/C); CTE_{OPM}, is at least about $7*10^{-6}$ (1/C); L_{OPM} is at least about 1 km; R_{Fmin} is at least about 5 cm; and, R_{coil} is at least about 10 cm; wherein the configuration is capable of transmitting a laser beam having at least 1 kW of power, without substantial power loss.

7. The method of claim **5**, wherein: R_{OPM} is at least about 1.0 mm; R_F is at least about 100 μm; the ΔT is at least about 50° C.; ϵ is at least about 0.01%; CTE_F is at least about $0.5*10^{-6}$ (1/C); CTE_{OPM} is at least about $7*10^{-6}$ (1/C); L_{OPM} is at least about 0.5 km; R_{Fmin} is at least about 5 cm; and, R_{coil} is at least about 10 cm; wherein the configuration is capable of transmitting a high power laser beam over great distances without substantial power loss.

8. The method of claim **5**, wherein the fiber core has a radius greater than about 75 μm.

9. The method of claim **5**, wherein the fiber core has a radius of greater than about 300 μm.

10. A method of transmitting laser energy over an optical fiber configuration, the method comprising:

a. providing a line structure,

b. the line structure comprising:

i. an optical fiber, a portion of the optical fiber comprising a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin});

ii. an outer protective member around the optical fiber portion, a portion of the outer protective member comprising a first end, a second end, and a length (L_{OPM}) defined between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F;

iii. the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous;

iv. the optical fiber configuration has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil});

v. wherein the L_F is greater than the L_{OPM}, so that $L_F - L_{OPM} = AFL$ (additional fiber length);

vi. the optical fiber taking a helical non-following path within the outer protective member; and,

vii. the AFL is equal to or between at least one of: an AFL[L] from Formulas 2 and 4 as defined in Applicants' Specification; or an AFL[%] from Formulas 1 and 3 as defined in Applicants' Specification;

viii. whereby, the optical fiber configuration is capable of transmitting at least about 1 kW of laser energy over great distances without substantial bending losses;

c. deploying the line structure;

d. transmitting laser energy through the optical fiber; and,

e. recovering the line structure.

11. A method of transmitting laser energy over an optical fiber configuration, the method comprising:

a. providing a line structure,

b. the line structure comprising:

i. an optical fiber, a portion of the fiber comprising a first end, a second end, a length (L_F) defined between the first and second optical fiber ends, and a fiber core, wherein the optical fiber has an outer radius (R_F), a coefficient of thermal expansion (CTE_F), and a minimum bend radius (R_{Fmin});

ii. an outer protective member around the optical fiber portion, a portion of the outer protective member comprising a first end, a second end, and a length (L_{OPM}) between the first and second outer protective member ends at ambient temperature and with no mechanical strain, wherein the outer protective member has an inner radius (R_{OPM}), a coefficient of thermal expansion (CTE_{OPM}), and the R_{OPM} is greater than the R_F;

iii. the first and second ends of the outer protective member and the first and second ends of the optical fiber are substantially coterminous;

iv. wherein the optical fiber configuration has a predetermined temperature range (ΔT), a predetermined mechanical strain (ϵ), and a predetermined inner radius of coil (R_{coil});

v. wherein the L_F is greater than the L_{OPM}, so that $L_F - L_{OPM} = AFL$ (additional fiber length);

vi. the optical fiber taking a sinusoidal non-following path within the outer protective member;

vii. the AFL is equal to or between at least one of: an AFL[L] from Formulas 9 and 11 as defined in Applicants' Specification; or an AFL[%] from Formulas 8 and 10 as defined in Applicants' Specification;

viii. whereby, the optical fiber configuration is capable of transmitting at least about 1 kW of laser energy over great distances without substantial bending losses;

b. deploying the line structure;

c. transmitting laser energy through the optical fiber; and,

d. recovering the line structure.

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